NASA CR-144938

UTEC CE 75-178

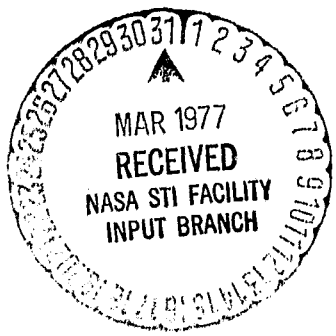
MEASURED PROPERTIES OF PROPELLANT FOR SOLID ROCKET BOOSTER OF ONE-EIGHTH SCALE DYNAMIC SHUTTLE MODEL

William L. Hufferd

Final Report

February 1977

NASA Grant NSG 1113



Submitted to

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

Civil Engineering Department
College of Engineering
University of Utah
Salt Lake City, Utah 84112

(NASA-CR-144938) MEASURED PROPERTIES OF PROPELLANT FOR SOLID ROCKET BOOSTER OF ONE-EIGHTH SCALE DYNAMIC SHUTTLE MODEL Final Report (Utah Univ.) 66 p HC A04/MF A01 CSCL 21I G3/28

N77-19272

Unclas 21646

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-144938		

4. Title and Subtitle	5. Report Date
MEASURED APROPERTIES OF PROPELLANT FOR SOLID ROCKET BOOSTER OF ONE-EIGHTH SCALE DYNAMIC SHUTTLE MODEL	February 1977
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
William L. Hufferd	UTEC CE 75-178
	10. Work Unit No.
9. Performing Organization Name and Address	11. Contract or Grant No.
College Of Engineering Civil Engineering Department University of Utah Salt Lake City, UT 84112	NSG-1113
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Contractor Report
National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Supercedes UTEC CE 75-178 dated November, 1975

Technical Monitor: John L. Sewall

16. Abstract

Static and dynamic material property tests were conducted on inert UTI-610 propellant to obtain basic mechanical response data for use in analysis of the one-eighth scale models of the Space Shuttle SRB being dynamically tested at the Langley Research Center.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Space Shuttle vibrations Viscoelasticity	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	60	$4.50

* For sale by the National Technical Information Service, Springfield, Virginia 22161

TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
II.	SUMMARY OF TEST RESULTS	1
III.	EXPERIMENTAL PROGRAM AND RESULTS	4
IV.	REPRESENTATION OF EXPERIMENTAL DATA	10
V.	CONCLUSIONS AND RECOMMENDATIONS	17
VI.	REFERENCES	19

TABLES

TABLE I -	CONSTANT STRAIN RATE TESTS	20
TABLE II -	STRESS RELAXATION TESTS	21
TABLE III-a	DYNAMIC TENSION TEST RESULTS AT A FREQUENCY OF 3.5 Hz	22
TABLE III-b	DYNAMIC TENSION TEST RESULTS AT A FREQUENCY OF 11 Hz	23
TABLE III-c	DYNAMIC TENSION TEST RESULTS AT A FREQUENCY OF 35 Hz	24
TABLE III-d	DYNAMIC TENSION TEST RESULTS AT A FREQUENCY OF 110 Hz	25
TABLE IV-a	DYNAMIC SHEAR TEST RESULTS AT A FREQUENCY OF 3.5 Hz	26
TABLE IV-b	DYNAMIC SHEAR TEST RESULTS AT A FREQUENCY OF 11 Hz	27
TABLE IV-c	DYNAMIC SHEAR TEST RESULTS AT A FREQUENCY OF 35 Hz	28
TABLE IV-d	DYNAMIC SHEAR TEST RESULTS AT A FREQUENCY OF 110 Hz	29
TABLE V -	RELATIVE HUMIDITY TESTS	30
TABLE VI-a	CONSTANT STRAIN RATE TESTS AT 0.05 (min^{-1}) AND 40% RELATIVE HUMIDITY	31
TABLE VI-b	CONSTANT STRAIN RATE TESTS AT 0.05 $(min)^{-1}$ AND 70% RELATIVE HUMIDITY	32
TABLE VI-c	CONSTANT STRAIN RATE TESTS AT 0.05 $(min)^{-1}$ AND 90% RELATIVE HUMIDITY	33
TABLE VII-a	CONSTANT STRAIN RATE TESTS AT 0.5 $(min)^{-1}$ AND 40% RELATIVE HUMIDITY	34
TABLE VII-b	CONSTANT STRAIN RATE TESTS AT 0.5 $(min)^{-1}$ AND 70% RELATIVE HUMIDITY	35
TABLE VII-c	CONSTANT STRAIN RATE TESTS AT 0.5 $(min)^{-1}$ AND 90% RELATIVE HUMIDITY	36

		Page
TABLE VIII-a	STRESS RELAXATION TESTS AT 40% RELATIVE HUMIDITY AND 25°C (3% Strain Level)	37
TABLE VIII-b	STRESS RELAXATION TESTS AT 40% RELATIVE HUMIDITY AND 25°C (3% Strain Level)	38
TABLE IX-a	STRESS RELAXATION TESTS AT 70% RELATIVE HUMIDITY AND 25°C (3% Strain Level)	39
TABLE IX-b	STRESS RELAXATION TESTS AT 70% RELATIVE HUMIDITY AND 25°C (3% Strain Level)	40
TABLE X -a	STRESS RELAXATION TESTS AT 90% RELATIVE HUMIDITY AND 25°C (3% Strain Level)	41
TABLE X -b	STRESS RELAXATION TESTS AT 90% RELATIVE HUMIDITY AND 25°C (3% Strain Level)	42
TABLE XI -a	DYNAMIC TENSION TESTS AT 40% RELATIVE HUMIDITY AND 25°C (1% Static Strain)	43
TABLE XI -b	DYNAMIC TENSION TESTS AT 70% RELATIVE HUMIDITY AND 25°C (1% Static Strain)	44
TABLE XI -c	DYNAMIC TENSION TESTS AT 90% RELATIVE HUMIDITY AND 25°C (1% Static Strain)	45
TABLE XII -a	DYNAMIC SHEAR TESTS AT 40% RELATIVE HUMIDITY AND 25°C (1% Static Strain)	46
TABLE XII -b	DYNAMIC SHEAR TESTS AT 70% RELATIVE HUMIDITY AND 25°C (1% Static Strain)	47
TABLE XII -c	DYNAMIC SHEAR TESTS AT 90% RELATIVE HUMIDITY AND 25°C (1% Static Strain)	48

FIGURES

		PAGE
FIGURE 1.	TEST SPECIMEN CONFIGURATIONS	49
FIGURE 2.	SCHEMATIC OF INSTRON UNIVERSIAL TESTING MACHINE	50
FIGURE 3.	SCHEMATIC OF RHEOVIBRON DYNAMIC TESTER	51
FIGURE 4.	TRUE-STRESS-VERSUS-STRAIN RESPONSE	52
FIGURE 5.	STRESS RELAXATION MODULUS VERSUS LOG TIME	53
FIGURE 6.	TIME-TEMPERATURE SHIFT FACTOR VERSUS TEMPERATURE	54
FIGURE 7.	MASTER STRESS RELAXATION MODULUS VERSUS TEMPERATURE REDUCED TIME	55
FIGURE 8.	REAL PART OF DYNAMIC TENSILE AND SHEAR MODULUS VERSUS FREQUENCY	56
FIGURE 9.	MASTER DYNAMIC MODULUS VERSES TEMPERATURE REDUCED FREQUENCY	57
FIGURE 10.	IMAGINARY PART OF DYNAMIC TENSILE & SHEAR MODULUS VERSUS FREQUENCY	58
FIGURE 11.	MASTER DYNAMIC LOSS MODULUS VERSUS TEMPERATURE REDUCED FREQUENCY	59
FIGURE 12.	LOSS TANGENT VERSUS TEMPERATURE REDUCED FREQUENCY	60

NOMENCLATURE

α_T = Temperature shift factor

E^* = Complex tensile modulus

E' = Real part of dynamic tensile modulus (storage modulus)

E'' = Imaginary part of dynamic tensile modulus (loss modulus)

E_o = Coefficient in power law representation of relaxation modulus

E_o' = Coefficient in power law representation of tensile storage modulus

E_e = Equilibrium relaxation modulus

E_k = Coefficients in Prony Series representation of modulus

G^* = Complex shear modulus

G' = Real part of dynamic shear modulus

G'' = Imaginary part of dynamic shear modulus

$H(t)$ = Heaviside unit step function

m = Log-log slope of real part of dynamic modulus curve

m = Exponent in modified power law representative of temperature shift function

n = Log-log slope of relaxation modulus curve

R = Rate of strain in constant strain-rate test

t = Time

T = Temperature

T_a = Empirical constant in modified power law representation of temperature shift function

T_r = Reference temperature

T_s = Empirical constant in WLF representation of temperature shift function

ε = Uniaxial (or shear) strain

$\tan \delta$ = Loss tangent

$\delta(t)$ = Dirac delta function

σ = uniaxial (a shear) stress

τ_k = Time constants in Prony Series representation of modulus

ν = Poisson's Ratio

ω = Circular frequency (in rad/sec in equations of section 4.1, in Hz elsewhere as noted)

I. INTRODUCTION

Characterization tests were conducted on the inert solid propellant cast in the 1/8 scale models of the space shuttle SRB being dynamically tested at the NASA Langley Research Center. Static and dynamic tests were carried out to evaluate the interconvertibility of static and dynamic response properties according to linear viscoelasticity theory. These tests were carried out at several temperatures and the time (frequency)-temperature superposition principle used to extend the range of applicability of the data. Some tests were also conducted to evaluate the effects of moisture (i.e., relative humidity) on propellant response and also the effects of static strain level.

The propellant, designated UTI-610, is an inert Polybutadiene Acrylo-Nitrile (PBAN) propellant with ammonium sulfate and sodium chloride replacing the normal oxidizer, ammonium perchlorate. The propellant samples and models were manufactured by the Chemical Systems Division of United Technologies Corporation*, Sunnyvale, California.

The following sections present a discussion and analysis of the test program and test results.

II. SUMMARY OF TEST RESULTS

2.1 Stress-relaxation tests in tension were conducted at several temperatures and strain levels and the temperature-reduced master stress relaxation modulus converted to dynamic tensile

*Formerly known as United Technology Center.

storage and loss moduli. With the exception of the 1% strain level tests at 4°C (40°F), the variation in modulus at 1 and 5% was within the data band scatter of the 3% strain level tests, which were used as the standard. Static relaxation modulus data converted to dynamic moduli did not agree well with the measured dynamic data, indicating that dynamic response properties should be obtained directly from dynamic tests.

2.2 Constant strain rate tests were conducted at various temperatures and the data converted to relaxation modulus. Typical of solid propellant data, the converted relaxation test data were higher than the values measured in stress relaxation tests.

2.3 Dynamic tensile and shear tests were conducted at various temperatures, frequencies, and strain levels. The shear and tension data were observed to have different time (frequency)-shift factors; however, plotted on a master temperature-reduced frequency plot, it was observed that $G' \tilde{=} E'/3$. The temperature shift factors for dynamic tension and stress relaxation test data agreed within experimental data scatter.

Static strain level within the range of 0.5 to 5% had no significant effect on dynamic moduli. Subsequent tests at 0.1% strain did show significant increases in dynamic stiffness

2.4 Tests were also conducted to evaluate the effect of moisture on constant strain rate, stress relaxation and dynamic tensile and shear test data. Dynamic tensile and shear tests conducted

at 40% and 70% relative humidity levels showed an initial increase in stiffness followed by a gradual decline with time, although no definite trend is immediately apparent. Significant decreases in stiffness were observed after only three days storage at 90% relative humidity. When placed in dessicant, these adverse effects were observed to be largely reversible; however, the rate of water removal was somewhat slower than the absorption rates.

Stress relaxation tests at 40% relative humidity showed a fifteen to twenty percent increase in stiffness following fourteen days storage and a softening upon seven days recovery in a dessicated atmosphere. No significant effect was observed for stress relaxation tests conducted under 70% relative humidity conditions. A substantial decrease in modulus was noted for tests conducted at 90% relative humidity.

The influence of moisture level on constant strain rate test results was evaluated in terms of maximum true stress and initial modulus. The data again indicated a slight increase in stiffness at 40% relative humidity, no significant effect at 70% relative humidity and substantial decrease in stiffness at 90% relative humidity.

The effects of moisture on UTI-610 propellant are somewhat atypical of the effects on live propellants. Live propellants generally show degradation in strength properties after

relatively short-term exposure to relative humidity levels in excess of about 50% R.H. Also maximum strength and stiffness properties are obtained under dessicated storage conditions. UTI-610 inert propellant appears to achieve its maximum strength in the neighborhood of 40 to 50% R.H., with essentially the same behavior observed by dessicated storage or storage at 70% relative humidity.

It is well known that oxidizer characteristics, in particular, polymer-oxidizer bonding properties significantly affect mechanical response. Therefore, it may be postulated that the observed influence of moisture on UTI-610 propellant response is due in large part to the combination of inert salts used in place of the oxidizer in the live propellant. The results of the test program are applicable to the model tests; however, they should not be extended to the full scale SRB without experimental confirmation with the actual SRB propellant.

2.5 Bulk compressibility tests were kindly carried out by Thiokol/Wasatch Division at no cost to the program. The bulk modulus was experimentally determined to be 1.84 MN/m^2 (267,000 psi) implying essentially incompressible material behavior over the frequency range of interest.

III. EXPERIMENTAL PROGRAM AND RESULTS

Propellant for the experimental characterization program was received from NASA, Langley Research Center in sealed one-half gallon milk cartons. Specimens 12.7 cm by 1.27 cm by 10.2 cm (0.5 in by 0.5 in by 4.0 in) were machined and wooden tabs bonded to the ends for the

static testing, i.e., constant strain-rate and stress relaxation tests. Thin slabs, .1 cm by .3 cm by .2 cm (0.04 in by 0.12 in by 0.8 in) were used for the dynamic tension tests and slabs .15 cm by .15 cm by .3 cm (0.06 in by 0.06 in by 0.12 in) were used for the dynamic shear tests. Test specimen configurations are shown in Figure 1.

A minimum of three and usually four replicate tests were carried out for each condition.

The test methods employed conformed to standard industry-wide practices [1-3]. An Instron Universal testing machine (Figure 2)with Missimer temperature conditioning box was used for static testing and a Rheovibron dynamic tester (Figure 3) was used for the dynamic tests.

Static and dynamic tests were conducted at -18°C (0°F), 4°C (40°F), 25°C (77°F) and 49°C (120°F) and time-temperature superposition used to evaluate the response properties at other temperatures and frequencies.

Constant strain rate tests were conducted at the strain rates and temperatures shown in Table I. True stress-strain response is shown in Figure 4.

Stress relaxation tests were conducted according to Table II. Relaxation modulus as a function of log time and strain level is shown in Figure 5.* With the exception of the one-percent strain level tests at 4°C the average values of the one and five percent strain level test data were within the $\pm$ 3 σ data band associated with the three percent strain level tests.

---

* In this and subsequent figures, logarithms are to the base 10, and the units indicated in the ordinate and/or abscissa apply to the corresponding exponential functions.

Figure 6 shows the time-temperature shift factor versus temperature as determined from stress-relaxation tests, dynamic tension and dynamic shear tests. Three-sigma limits are also shown for the stress-relaxation determined shift factors.

Thermorheologically simple material behavior requires time-temperature shift factors to be identical, irrespective of how they were determined. However, it may be noted in Figure 6 that the shift factors determined from dynamic shear tests do not agree with those determined from stress-relaxation or dynamic tension tests, which are in reasonable agreement with each other. The reason for this discrepancy is not known, although it is probably associated with some deficiency in the dynamic shear test procedure. The shift factors associated with the stress relaxation tests were used to superpose the relaxation modulus and dynamic tension test results whereas the shift factors obtained from dynamic shear tests were used to develop a master dynamic shear modulus curve.

Figure 7 presents the master relaxation modulus as a function of temperature-reduced time, t/a_T. Figure 7 also shows the master relaxation modulus obtained from the constant strain rate test data shown in Figure 4 using the relation,

$$E_{rel}(t/a_T) = \left.\frac{d\sigma(t/a_T)}{d\epsilon}\right|_{\epsilon = Rt/a_T}$$

where R is the rate of straining. It may be observed that the modulus obtained from the constant strain rate tests is substantially higher than that obtained from stress relaxation tests, particularly at short times or low temperatures.

Dynamic tension tests were carried out at 3.5, 11, 35 and 110 Hz and 0.1, 0.5, 1.0, 2.5 and 5.0 percent static strain levels at 18¼C (0°F), 4°C (40°F), 25°C (77°F) and 49°C (120°F). Dynamic shear tests were carried out at the same frequencies and temperatures at strain levels of 0.5, 1.0, 2.5 and 5.0 percent pre-imposed static strain.

Dynamic tension results are tabulated in Tables III-a through III-d and dynamic shear results are tabulated in Tables IV-a through IV-d. The notation in Tables III and IV is derived from the following representations for complex modulus:

$$E^*(\omega) = E' + iE''$$

$$G^*(\omega) = G' + iG''$$

$$\tan \delta = \frac{E''}{E'} \text{ or } \frac{G''}{G'}$$

$$|E| = \sqrt{(E')^2+(E'')^2}$$

$$|G| = \sqrt{(G')^2+(G')^2}$$

A fixed half-amplitude dynamic displacement of 50 μm was used for all dynamic tests. The length of the dynamic specimens for the 0.1 percent strain level tests was 2 inches (5 cm) rather than the 0.8 inches (2 cm) shown in Figure 1. For this test the dynamic strain level was equal to the imposed static strain of 0.1 percent. In all other dynamic tests the dynamic strain level varied between 0.23 and 0.25 percent.

It may be observed from Tables III and IV that a gradual decline or softening of the dynamic stiffness occurs with increasing static strain level. The maximum dynamic tensile modulus occurs for a static strain of 0.1 percent where the dynamic strain is also equal to this value. Typical of live propellant behavior dynamic moduli increase for decreasing static strain and/or dynamic strain levels.

The measured real part of the dynamic tensile and shear moduli are presented in Figure 8 for a static strain level of 0.5 percent. A greater amount of data scatter may be observed in the dynamic shear data; particularly at 11 Hz.

Finally, Figure 9 presents the master dynamic tensile and shear moduli versus temperature reduced frequency. The dynamic tensile modulus, calculated from stress relaxation test data and constant strain rate test data is also shown for comparison. It may be noted that the dynamic moduli calculated in this fashion do not agree with the measured dynamic data. The master dynamic shear modulus curve shown in Figure 9 was obtained from the data presented in Figure 8 using the frequency-temperature shift factors developed from the dynamic shear tests and previously presented in Figure 6. Although considerable data scatter exists, it may be seen that the master dynamic shear modulus is approximately one-third of the value of the measured tensile modulus, indicating nearly incompressible material behavior.

The imaginary part of the dynamic tensile and shear modulus, E" and G" is presented in Figure 10 as a function of frequency, and in Figure 11 as a function of temperature-reduced frequency. The variability and data scatter in G" indicate that the shear test results

are not likely to be truly representative of the propellant's dynamic stress behavior. The anomalous shear behavior is attributed to coupling between the shim-stock support and glue and the propellant (see Figure 1).

Figure 12 presents the loss tangent in tensile and shear versus temperature reduced frequency. The shear loss tangent should not be used in an analysis due to the aforementioned data scatter in the shear tests. From Figure 12 a value of tan δ between .5 and .525 appears to be adequate for the tensile loss tangent in the frequency range of interest (i.e., between 1 and 1000 Hz).

Additional constant strain rate, stress relaxation and dynamic tension and shear tests were conducted according to Table V to investigate the influence of moisture on the inert propellant response. Constant strain rate tests were reduced according to the maximum true stress, strain at maximum true stress and initial modulus [1]. Test results are presented in Tables VI and VII.

Stress relaxation test results at 40, 70, and 90 percent relative humidity levels are presented in Tables VIII through X, and dynamic test results are presented in Tables XI and XII.

IV. REPRESENTATION OF EXPERIMENTAL DATA

4.1 Theoretical Considerations

All of the tests employed during this program can be used to deduce the dynamic moduli for a linear viscoelastic material. The discrepancies noted previously between some of the interconversions is an indication of nonlinear material response and the need to determine dynamic properties directly. Still it is instructive to develop those relationships commonly used in converting static data to dynamic response data. The essential steps for accomplishing this are described in the following paragraphs [4].

A convenient representation for the uniaxial (or shear) stress, σ, in a linear viscoelastic material is the so-called integral or relaxation formulation which, for the isothermal case, has the form

$$\sigma(t) = \int_{-\infty}^{t} E_{rel}(t-\tau) \frac{d\varepsilon(\tau)}{d\tau} d\tau \qquad (1)$$

Where $E_{rel}(t-\tau)$ is the relaxation modulus in tension (or shear) and $\varepsilon(t)$ is the imposed strain history.

The relaxation modulus is defined as the stress decay associated with a step input strain ε_o. With $\varepsilon=\varepsilon_o H(\tau)$, Eq. (1) becomes

$$\sigma(t) = \int_{-\infty}^{t} E_{rel}(t-\tau)\, \varepsilon_o\, \delta(\tau)\, d\tau$$

or

$$\frac{\sigma(t)}{\varepsilon_o} = E_{rel}(t),$$

where $H(\tau)$ is the Heaviside unit step function and $\delta(\tau)$ is the Dirac delta function.

For a constant strain rate test, with strain rate R (ε=Rt), Eq. (1) yields

$$\sigma(t) = R \int_0^t E_{rel}\,(t-\tau)\,d\tau \qquad (2)$$

Differentiating Eq. (2) with respect to t gives

$$\frac{d\sigma(t)}{dt} = R\,E_{rel}\,(0) + R \int_0^t \frac{dE_{rel}\,(t-\tau)}{dt}\,d\tau$$

$$= R\,E_{rel}\,(0) - R \int_0^t \frac{dE_{rel}\,(t-\tau)}{d\tau}\,d\tau$$

$$= R\,E_{rel}\,(t)$$

or

$$\left.\frac{d\sigma(t)}{d\varepsilon}\right|_{\varepsilon = Rt} = E_{rel}\,(t) \qquad (3)$$

Thus, the relaxation modulus can be deduced from differentiation of the stress-strain curve in a constant strain rate test.

The dynamic modulus, $E^*(\omega)$, is defined as a complex quantity

$$E^* = E' + i\,E''$$

Where E' is referred to as the storage modulus and E" is referred to as the loss modulus. Tan δ = E"/E' is known as the loss tangent and is a measure of energy dissipation; that is, the damping characteristics of the material. For some viscoelastic materials $E_{rel}(t) = E'(\omega)$.

The dynamic modulus, E*, is defined as the stress response to a forced harmonic strain input. Thus, from Eq. (1) for $\varepsilon = \varepsilon_0 e^{i\omega t}$, where ω is the circular frequency,

$$\sigma(t) = \varepsilon_o \, i\omega \int_{-\infty}^{t} E_{rel}\,(t-\tau)\, e^{i\omega\tau}\, d\tau \qquad (4)$$

Performing a change of variables by letting $u = t - \tau$, Eq. (4) becomes

$$\sigma(t) = \varepsilon_o \, i\omega \, e^{i\omega t} \int_{o}^{\infty} E_{rel}\,(u)\, e^{-i\omega u}\, du \qquad (5)$$

or

$$E^*(\omega) = \frac{\sigma(t)}{\varepsilon_o e^{i\omega t}} = i\omega \int_{o}^{\infty} E_{rel}\,(u)\, e^{-i\omega u}\, du \qquad (6)$$

Recalling the definition of the Laplace Transform, Eq. (6) is seen to be

$$E^*(\omega) = i\omega \mathcal{L}[E_{rel}(u)] \Big|_{u=i\omega}$$

Thus, if the stress relaxation modulus is known, the dynamic modulus can be obtained by taking the Laplace transform, setting the transform variable equal to $(i\omega)$ and multiplying the result by $(i\omega)$. This observation is particularly useful if an exponential series (Prony Series or Dirichlet series) is used to represent the relaxation modulus. In this case,

$$E_{rel}\,(t) = E_e + \sum_{k=1}^{n} E_k \exp\,(-t/\tau_k) \qquad (7)$$

Where E_e is the equilibrium relaxation modulus, and E_k and τ_k are constants chosen to fit the experimental data. E' and E" are readily determined from Eq. (7) to be

$$E'\,(\omega) = E_e + \sum_{k=1}^{n} \frac{E_k\,(\omega\tau_k)^2}{1 + (\omega\tau_k)^2} \qquad (8)$$

and

$$E''\,(\omega) = \sum_{k=1}^{n} \frac{E_k\,(\omega\tau_k)}{1 + (\omega\tau_k)^2} \qquad (9)$$

The above analyses apply to isothermal, i.e., constant temperature conditions. In practice, it is impossible to obtain either relaxation data or dynamic data over the time scales and frequency ranges of practical interest in a solid rocket motor. In order to obtain data in these ranges the concept of time-temperature superposition is routinely employed [1-4].

It has been widely found that temperature has the effect of expanding or contracting the time scale of response viscoelastic materials and that an equivalence between time or frequency and temperature exists. Time and frequency are roughly the inverse of one another so that short time or high frequency response at one temperature corresponds to longer time or lower frequency response at a lower temperature. The converse holds true at higher temperatures. Thus, by obtaining the propellant response at several temperatures, a time-temperature shift function, a_T, relating the equivalence of time or frequency and temperature can be experimentally determined by horizontally "shifting" the test data so that it superimposes to form a single curve at some given reference temperature, usually 21 to 25°C. The resulting curve is known as the "master" response curve and is expressed in terms of temperature-reduced time, t/a_T, in the case of the master relaxation modulus curve, or in terms of temperature-reduced frequency, ωa_T, in the case of the master dynamic moduli curves [1-4].

Thus, the previous analyses remain valid in terms of the master relaxation and dynamic moduli if time, t, and frequency, ω, in the previous expressions are replaced by temperature-reduced time, t/a_T, and frequency-reduced time, ωa_T, respectively.

4.2 EXPLICIT REPRESENTATION OF EXPERIMENTAL DATA

The linear behavior of the relaxation modulus versus temperature reduced time, t/a_T, on a log-log plot suggests a power law representation of the form

$$E(t/a_T) = E_0(t/a_T)^{-n}$$

For the relaxation modulus determined from conventional stress relaxation tests, E_0 and n were determined from Figure 7 to be

$$E_0 = 1050 \text{ psi} = 7239 \text{ kN/m}^2$$

$$n = 0.11$$

where n is the slope of the relaxation modulus curve. For the relaxation modulus determined as the derivative of constant strain rate tests, also shown in Figure 7,

$$E_0 = 1550 \text{ psi} = 10\ 700 \text{ kN/m}^2$$

$$n = 0.14$$

For conversion to dynamic response data it is more convenient to use the Prony Series representation given by Eq. (7). For this purpose, the equilibrium modulus was estimated to be 160 psi (1100 kN/m^2) and a fourteen term Prony Series was used with the following values:

τ_k^{-1}	E_k (psi)	E_k (kN/m^2)
$5x10^{-7}$	140	965
$5x10^{-6}$	25	172
$5x10^{-5}$	125	862
$5x10^{-4}$	115	793
$5x10^{-3}$	100	690
$5x10^{-2}$	280	1930
$5x10^{-1}$	375	2590
5	95	655
$5x10^{1}$	510	3520
$5x10^{2}$	525	3620
$5x10^{3}$	720	4960
$5x10^{4}$	785	5410
$5x10^{5}$	1490	10300
$5x10^{6}$	825	5690

The conversion of the relaxation modulus to dynamic moduli is accomplished using Eqs. (8) and (9). The real part of the dynamic modulus, $E'(\omega)$, calculated according to Eq. (8) has been presented in Figure 9. With the discrepancy noted in Figure 9 between the measured and calculated E', it is more appropriate to obtain a direct representation of the measured E' in the form of a power law

$$E'(\omega a_T) = E'_o \, (\omega a_T)^m \tag{10}$$

with m again the slope on a log E' versus log ωa_T plot. Fitting Eq. (10) to the data presented in Figure 9 yields

$$E'_o = 1140 \text{ psi}$$
$$m = 0.26$$

over the reduced frequency range 0 to 1000 Hz.

It is also possible to obtain analytical representation for the temperature shift factor, a_T. A common representation for amorphous polymers is the well-known WLF equation

$$\log a_T = \frac{-8.86(T-Ts)}{101.6 + T-Ts} \tag{11}$$

where T is measured in degrees Kelvin. A comparison of the agreement of Eq. (11), choosing Ts = 323°K (25°C), with the experimentally determined shift-factors is shown in Figure 6. The agreement is not exact; however, the analytical values are with the $\pm 3\sigma$ limits.

A somewhat better representation of the temperature shift factor for a filled propellant is obtained using the modified power law representation

$$a_T = \left(\frac{T_R - T_a}{T - T_a} \right)^m \tag{12}$$

where T_R is the reference temperature, 25°C in our case, and T_a is a characteristic temperature. The agreement of Eq. (12) with the experimentally determined shift factors is also shown in Figure 6. Values of 50°C and 15 were used for T_a and m in Eq. (12) for the purposes of this comparison. It may be noted that Eq. (12) represents the mean experimental data more accurately than does Eq.(11).

Based on the discrepancies and scatter associated with the dynamic shear tests it is recommended that a loss tangent between 0.5 and 0.525 be used for dynamic tension and shear analyses.

V. CONCLUSIONS AND RECOMMENDATIONS

Results of characterization tests conducted on the inert solid propellant in the one-eighth scale dynamic models of the space shuttle SRB have been presented. Based on the fact that converted static test data did not agree with the measured dynamic test data it is concluded that dynamic tests should be conducted for determining properties for dynamic analyses of the SRB.

Furthermore, due to the data scatter associated with dynamic shear tests it is recommended that dynamic tensile data be used in SRB model analyses and that the shear modulus be assumed to be one-third that of the tensile modulus. Separate bulk modulus tests indicate that the propellant is nearly incompressible ($\nu \tilde{=} 0.5$) so that this assumption should be reasonable.

For analysis purposes, in the range of 1 to 1000 Hz, it is recommended that $E'(\omega)$ be determined according to Eq. (10) and that $\tan \delta$ be taken equal to 0.5.

As far as the dynamic model tests are concerned, there is some evidence that hardening of the propellant occurs in the range of 40 to 70 percent relative humidity. This hardening can be accounted for in the dynamic analyses of the SRB models using the moisture data presented herein.

Initially proposed preliminary dynamic analyses of the SRB models were not conducted due to the additional effort, beyond that first estimated, in carrying out the experimental program.

VI. REFERENCES

1. ICRPG Solid Propellant Mechanical Behavior Manual, CPIA Publication No. 21, The Johns Hopkins University, 1963.

2. Fitzgerald, J. E., and Hufferd, W. L., Handbook for the Engineering Structural Analysis of Solid Propellants, CPIA Publication No. 214, The Johns Hopkins University, May 1971.

3. JANNAF Solid Propellant Structural Integrity Handbook, edited by W. L. Hufferd and J. E. Fitzgerald, CPIA Publication No. 230, The Johns Hopkins University, September 1972.

4. Hufferd, W. L., "Creep and Stress Relaxation of Polymers", Proceedings of the Polymer Conference Series on Mechanical Behavior, University of Utah, UTEC CE 72-096, June 1972.

TABLE I

CONSTANT STRAIN RATE TESTS

Strain Rate $(min)^{-1}$ \ Temperature (°C)	-18	4	25	49
5			X	X
0.5	X	X	X	X
0.05		X	X	
0.005	X		X	

TABLE II

STRESS RELAXATION TESTS

Strain Level (%) \ Temperature (°C)	-18	4	25	49
1		X	X	
3	X	X	X	X
5			X	X

TABLE III-a

DYNAMIC TENSION TEST RESULTS
AT A FREQUENCY OF 3.5 Hz

STATIC STRAIN (%)	TEMPERATURE (°C)	tan δ	$\lvert E \rvert$ (MN/m^2)	E' (MN/m^2)	E" (MN/m^2)
0.1	-18	0.32	313	299	95.1
	4	0.47	65.3	59.0	27.8
	25	0.45	16.5	15.0	6.74
	49	0.38	3.92	3.68	1.36
0.5	-18	0.32	179	170	54.4
	4	0.45	45.6	41.5	18.8
	25	0.43	13.5	12.4	5.3
	49	0.32	5.91	5.58	1.82
1.0	-18	0.33	175	166	53.7
	4	0.45	43.8	40	17.9
	25	0.43	12.6	11.6	4.67
	49	0.30	5.42	5.17	1.58
2.5	-18	0.34	166	158	52.3
	4	0.45	39.9	36.6	16.3
	25	0.42	11.6	10.53	4.34
	49	0.30	4.68	4.48	1.35
5.0	-18	0.35	138	131	42.3
	4	0.43	34.8	32.1	13.4
	25	0.39	10.9	9.42	3.11
	49	0.26	4.0	3.85	1.09

TABLE III-b

DYNAMIC TENSION TEST RESULTS
AT A FREQUENCY OF 11 Hz

STATIC STRAIN (%)	TEMPERATURE (°C)	tan δ	$\|E\|$ (MN/m^2)	E' (MN/m^2)	E'' (MN/m^2)
0.1	-18	0.34	333	315	107
	4	0.50	70.8	63.3	31.5
	25	0.47	19.7	17.8	8.35
	49	0.42	6.75	6.17	2.72
0.5	-18	0.33	207	197	63.3
	4	0.48	53.8	48.5	23.5
	25	0.48	15.0	13.6	6.49
	49	0.38	5.99	5.6	2.11
1.0	-18	0.33	214	204	66.4
	4	0.49	52.5	47.2	23.2
	25	0.47	14.0	12.6	6.0
	49	0.37	6.22	5.85	2.13
2.5	-18	0.32	213	204	62.6
	4	0.48	55.8	50.33	24.2
	25	0.47	14.7	13.2	6.32
	49	0.36	6.48	6.08	2.24
5.0	-18	0.33	185	177	52.5
	4	0.46	48.5	44.0	20.5
	25	0.44	13.8	12.6	5.64
	49	0.35	5.88	5.54	1.97

TABLE III-c

DYNAMIC TENSION TEST RESULTS
AT A FREQUENCY OF 35 Hz

STATIC STRAIN (%)	TEMPERATURE (°C)	tan δ	$\|E\|$ (MN/m^2)	E' (MN/m^2)	E'' (MN/m^2)
0.1	-18	0.42	405	374	153
	4	0.68	71.2	58.9	39.7
	25	1.08	25.0	17.2	18.0
	49	0.64	8.8	7.43	4.72
0.5	-18	0.26	269	260	67.3
	4	0.55	75.2	65.9	36.2
	25	0.62	21.8	18.5	11.4
	49	0.47	8.37	7.56	3.57
1.0	-18	0.26	276	267	69.3
	4	0.55	75.2	65.9	36.2
	25	0.62	21.8	18.5	11.4
	49	0.47	8.37	7.56	3.57
2.5	-18	0.26	263	254	66.1
	4	0.52	76.3	68	34.7
	25	0.58	21.6	18.8	10.7
	49	0.46	8.66	7.85	3.64
5.0	-18	0.27	243	234	61.8
	4	0.48	71	64	30.8
	25	0.50	18.6	16.7	8.24
	49	0.45	7.92	7.23	3.24

TABLE III-d

DYNAMIC TENSION TEST RESULTS
AT A FREQUENCY OF 110 Hz

STATIC STRAIN (%)	TEMPERATURE (°C)	tan δ	$\|E\|$ (MN/m^2)	E' (MN/m^2)	E'' (MN/m^2)
0.1	-18	0.375	512	482	171
	4	1.1	120	87.2	78.1
	25	1.24	33.5	27.1	24.2
	49	1.25	12.3	8.06	8.94
0.5	-18	0.27	316	304	81.4
	4	0.53	102	90.4	48.0
	25	0.59	30.2	26.0	15.4
	49	0.54	12.2	10.8	5.81
1.0	-18	0.26	328	308	80.7
	4	0.53	105	92.6	49.2
	25	0.58	31.1	26.8	15.8
	49	0.53	12.2	10.7	5.72
2.5	-18	0.25	324	314	75.8
	4	0.50	108	96.9	47.8
	25	0.56	31.6	27.6	15.5
	49	0.51	12.3	11.3	5.59
5.0	-18	0.26	299	289	73.4
	4	0.48	103	92.0	44.4
	25	0.52	30.3	26.8	14.0
	49	0.48	11.7	10.6	5.12

TABLE IV-a

DYNAMIC SHEAR TEST RESULTS
AT A FREQUENCY OF 3.5 Hz

STATIC STRAIN (%)	TEMPERATURE (°C)	tan δ	$\lvert G \rvert$ (MN/m^2)	G' (MN/m^2)	G" (MN/m^2)
0.5	-18	0.052	11.2	11.2	0.59
	4	0.174	8.06	7.94	1.33
	25	0.29	4.33	4.16	1.18
	49	0.31	1.89	1.81	0.55
1.0	-18	0.061	11.0	11.0	0.67
	4	0.21	7.35	7.16	1.49
	25	0.33	3.44	3.27	1.05
	49	0.31	1.71	1.64	0.51
2.5	-18	0.061	11.1	11.1	0.68
	4	0.21	7.29	7.13	1.48
	25	0.33	3.26	3.12	1.01
	49	0.32	1.59	1.52	0.48
5.0	-18	0.059	11.1	11.1	0.66
	4	0.205	7.35	7.2	1.45
	25	0.33	3.26	3.1	1.01
	49	0.32	1.54	1.47	0.47

TABLE IV-b

DYNAMIC SHEAR TEST RESULTS AT
A FREQUENCY OF 11 Hz

STATIC STRAIN (%)	TEMPERATURE (°C)	tan δ	$\|G\|$ (MN/m^2)	G' (MN/m^2)	G" (MN/m^2)
0.5	-18	0.023	12.63	12.6	0.30
	4	0.10	10.5	10.4	1.08
	25	0.24	6.5	6.32	1.51
	49	0.31	3.42	3.28	0.99
1.0	-18	0.023	12.8	12.8	0.31
	4	0.1	10.4	10.3	1.14
	25	0.27	6.0	5.78	1.55
	49	0.33	2.99	2.67	0.95
2.5	-18	0.023	12.8	12.8	0.31
	4	0.11	10.5	10.4	1.11
	25	0.27	5.86	5.64	1.59
	49	0.34	2.82	2.67	0.91
5.0	-18	0.023	12.8	12.8	0.30
	4	0.093	10.5	10.4	1.02
	25	0.28	5.55	5.33	1.53
	49	0.34	2.58	2.43	0.85

TABLE IV-c

DYNAMIC SHEAR TEST RESULTS
AT A FREQUENCY OF 35 Hz

STATIC STRAIN	TEMPERATURE (°C)	tan δ	$\lvert G \rvert$ (MN/m^2)	G' (MN/m^2)	G" (MN/m^2)
0.5	-18	0.036	14.67	14.67	0.58
	4	0.15	11.5	11.4	1.82
	25	0.31	6.26	5.97	1.85
	49	0.41	2.46	2.29	0.91
1.0	-18	0.045	14.3	14.3	0.68
	4	0.22	9.83	9.58	2.18
	25	0.41	3.8	3.52	1.43
	49	0.42	1.59	1.47	0.61
2.5	-18	0.05	14.0	13.9	0.75
	4	0.23	9.13	8.85	2.16
	25	0.44	3.28	3.01	1.28
	49	0.42	1.23	1.13	0.47
5.0	-18	0.072	13.2	13.2	1.03
	4	0.28	7.8	7.5	2.09
	25	0.45	2.97	2.72	1.23
	49	0.42	0.99	0.91	0.37

TABLE IV-d

DYNAMIC SHEAR TEST RESULTS AT A FREQUENCY OF 110 Hz

STATIC STRAIN (%)	TEMPERATURE (°C)	tan δ	$\|G\|$ (MN/m^2)	G' (MN/m^2)	G" (MN/m^2)
0.5	-18	0.036	22.0	22.0	0.84
	4	0.12	18.0	17.9	2.13
	25	0.29	10.9	10.4	2.98
	49	0.41	4.99	4.65	1.91
1.0	-18	0.046	22.2	22.2	1.08
	4	0.14	17.6	17.4	2.50
	25	0.34	9.77	9.25	3.08
	49	0.43	4.48	4.12	1.77
2.5	-18	0.046	22.4	22.4	1.12
	4	0.15	17.2	17.0	2.58
	25	0.35	9.33	8.8	3.09
	49	0.45	4.01	3.65	1.66
5.0	-18	0.049	22.0	22.0	1.14
	4	0.16	16.8	16.6	2.66
	25	0.37	8.49	7.96	2.94
	49	0.46	3.07	2.79	1.30

TABLE V

RELATIVE HUMIDITY TESTS

Exposure Time (Days) \ Relative Humidity (%)	40	70	90
1	X	X	X
3	X	X	X
7		X	X
14	X	X	X
Recovery Time at 0% RH Following 14 Days Exposure			
1	X	X	X
3	X	X	X
7	X	X	X

Tests:

(1) Constant strain rate at .05 and .5 $(min)^{-1}$ and 25°C

(2) Stress relaxation at 3% strain and 25°C

(3) Dynamic tension and shear at 3.5, 11, 35, and 110 Hz, 1% strain and 25°C

TABLE VI-a

CONSTANT STRAIN RATE TESTS AT

0.05 (min^{-1}) AND 40% RELATIVE HUMIDITY

STORAGE CONDITION	STRAIN AT MAXIMUM TRUE STRESS (PERCENT)				MAXIMUM TRUE STRESS (kN/m^2)				INITIAL MODULUS (kN/m^2)			
	1	2	3	AVG	1	2	3	AVG	1	2	3	AVG
CONTROL	18.0	16.0	15.0	16.3	958	786	869	869	4740	5570	7240	5850
1 Day at 40% RH	14.1	12.5	13.5	13.4	765	667	724	717	6220	5200	2090	5500
3 Days at 40% RH	13.3	15.0	15.0	14.4	793	634	717	696	7380	5090	5090	5850
7 Days at 40% RH	13.0	13.0	14.0	13.3	793	758	696	757	7720	5760	5990	6500
14 Days at 40% RH	12.5	14.0	13.5	13.3	827	745	800	793	7930	6780	6110	6960
14 Days at 40% RH & 1 Day at 0% RH	13.5	11.0	13.5	12.7	834	710	670	738	7450	7240	6780	7170
14 Days at 40% RH & 3 Days at 0% RH	13.5	14.5	13.5	13.8	793	738	676	738	7100	6780	6450	6780
14 Days at 40% RH & 7 Days at 0% RH	13.8	13.8	13.0	13.5	672	724	658	685	6780	6220	6330	6450

TABLE VI-b

CONSTANT STRAIN RATE TESTS AT

0.05 $(min)^{-1}$ AND 70% RELATIVE HUMIDITY

STORAGE CONDITION	STRAIN AT MAXIMUM TRUE STRESS (PERCENT)				MAXIMUM TRUE STRESS (kN/m^2)				INITIAL MODULUS (kN/m^2)			
	1	2	3	AVG	1	2	3	AVG	1	2	3	AVG
CONTROL	18.0	16.0	15.0	16.3	958	786	869	869	4740	5570	7240	5850
1 Day at 70% RH	14.0	15.0	15.0	14.7	736	672	596	668	6220	6330	6110	6220
3 Days at 70% RH	15.0	15.0	15.0	15.0	768	698	771	746	6780	6780	6220	6590
7 Days at 70% RH	16.0	15.0	16.0	15.7	633	653	656	647	6780	6220	5990	6330
14 Days at 70% RH	15.0	17.0	17.5	16.5	628	694	687	670	6450	5650	5540	5880
14 Days at 70% RH & 1 Day at 0% RH	15.0	15.0	16.0	15.3	609	698	637	648	6450	6220	5310	5990
14 Days at 70% RH & 3 Days at 0% RH	15.0	17.5	16.0	16.2	736	778	681	731	6330	5650	5650	5880
14 Days at 70% RH & 7 Days at 0% RH	13.8	16.0	14.0	14.6	747	736	616	700	6670	6220	6220	6370

TABLE VI-c

CONSTANT STRAIN RATE TESTS AT

0.05 $(min)^{-1}$ AND 90% RELATIVE HUMIDITY

STORAGE CONDITION	STRAIN AT MAXIMUM TRUE STRESS (PERCENT)				MAXIMUM TRUE STRESS (kN/m^2)				INITIAL MODULUS (kN/m^2)			
	1	2	3	AVG	1	2	3	AVG	1	2	3	AVG
CONTROL	18.0	16.0	15.0	16.3	958	786	869	869	4740	5570	7240	5850
1 Day at 90% RH	15.0	14.0	14.0	14.3	647	566	560	591	6900	5880	5990	6260
3 Days at 90% RH	15.0	13.5	16.0	14.8	580	435	560	525	5880	5430	4860	5390
7 Days at 90% RH	17.5	13.8	15.0	15.4	483	367	402	417	4980	3960	4070	4340
14 Days at 90% RH	13.5	12.5	15.0	13.7	279	239	285	268	3620	3280	2940	3280
14 Days at 90% RH & 1 Day at 0% RH	13.5	13.5	12.0	13.0	316	272	256	281	4070	2940	3050	3350
14 Days at 90% RH & 3 Days at 0% RH	14.0	12.0	12.5	12.8	283	229	295	269	3960	2940	3390	3430
14 Days at 90% RH & 7 Days at 0% RH	11.5	11.0	11.5	11.3	301	303	271	292	3730	4180	3390	3770

TABLE VII-a

CONSTANT STRAIN RATE TESTS AT

0.5 $(min)^{-1}$ AND 40% RELATIVE HUMIDITY

STORAGE CONDITION	STRAIN AT MAXIMUM TRUE STRESS (PERCENT)				MAXIMUM TRUE STRESS (kN/m^2)				INITIAL MODULUS (kN/m^2)			
	1	2	3	AVG	1	2	3	AVG	1	2	3	AVG
CONTROL	19.0	18.0	17.0	18.0	1270	1050	1170	1160	7740	10,700	11,700	10,000
1 Day at 40% RH	16.5	14.5	15.0	15.3	979	945	869	931	7290	8,930	9,050	8,630
3 Days at 40% RH	16.5	16.0	16.0	16.2	965	1030	1150	1050	9500	9,050	8,250	8,930
7 Days at 40% RH	14.0	13.5	15.0	14.2	1050	986	1050	1030	9950	9,950	7,920	9,270
14 Days at 40% RH	15.0	15.0	17.5	15.8	1060	1080	1050	1060	1,0700	9,720	7,920	9,450
14 Days at 40% RH & 1 Day at 0% RH	15.0	14.0	17.5	15.5	993	889	986	956	8930	8,590	8,480	8,670
14 Days at 40% RH & 3 Days at 0% RH	17.0	18.5	14.0	16.5	1010	972	958	980	9050	9,050	8,480	8,860
14 Days at 40% RH & 7 Days at 0% RH	15.0	14.3	15.0	14.8	1010	979	862	950	9050	8,480	7,920	8,480

TABLE VII-b

CONSTANT STRAIN RATE TESTS AT

0.5 $(min)^{-1}$ AND 70% RELATIVE HUMIDITY

STORAGE CONDITION	STRAIN AT MAXIMUM TRUE STRESS (PERCENT)				MAXIMUM TRUE STRESS (kN/m^2)				INITIAL MODULUS (kN/m^2)			
	1	2	3	AVG	1	2	3	AVG	1	2	3	AVG
CONTROL	19.0	18.0	17.0	18.0	1270	1050	1170	1160	7740	10700	11700	10000
1 Day at 70% RH	17.0	17.5	18.5	17.7	1010	903	1080	998	8480	8590	8590	8550
3 Days at 70% RH	15.0	18.5	16.0	16.5	1010	948	985	981	9160	9050	8590	8930
7 Days at 70% RH	16.5	17.5	17.5	17.2	932	868	1000	933	9050	8590	8480	8710
14 Days at 70% RH	17.5	17.5	17.5	17.5	885	907	784	859	8140	8140	7460	7910
14 Days at 70% RH & 1 Day at 0% RH	17.5	17.5	17.0	17.3	843	839	942	875	7240	7240	7920	7470
14 Days at 70% RH & 3 Days at 0% RH	17.5	17.5	17.5	17.5	849	881	979	903	8370	8250	8250	8290
14 Days at 70% RH & 7 Days at 0% RH	15.0	16.8	16.5	16.1	913	973	945	944	9610	6710	8370	8230

TABLE VII-c

CONSTANT STRAIN RATE TESTS AT

0.5 $(min)^{-1}$ AND 90% RELATIVE HUMIDITY

STORAGE CONDITION	STRAIN AT MAXIMUM TRUE STRESS (PERCENT)				MAXIMUM TRUE STRESS (kN/m^2)				INITIAL MODULUS (kN/m^2)			
	1	2	3	AVG	1	2	3	AVG	1	2	3	AVG
CONTROL	19.0	18.0	17.0	18.0	1270	1050	1170	1160	7740	10700	11700	10000
1 Day at 90% RH	20.0	19.0	16.0	18.3	953	994	825	924	8480	7920	7920	8110
3 Days at 90% RH	20.0	20.0	15.0	18.3	837	821	660	773	8250	7800	7350	7800
7 Days at 90% RH	17.5	17.5	--	17.5	557	596	--	577	6330	6110	--	6220
14 Days at 90% RH	14.0	15.0	12.5	13.8	330	362	313	335	4520	4410	3510	4150
14 Days at 90% RH & 1 Day at 0% RH	14.0	14.0	14.0	14.0	340	393	384	372	4520	5090	4300	4640
14 Days at 90% RH & 3 Days at 0% RH	12.0	10.0	12.0	10.7	355	325	324	335	5540	5650	4180	5120
14 Days at 90% RH & 7 Days at 0% RH	11.5	11.5	12.5	11.8	326	415	413	385	5200	6220	4980	5470

TABLE VIII-a

STRESS RELAXATION TESTS

AT 40% RELATIVE HUMIDITY AND 25°C (3% Strain Level)

TIME (seconds)	ZERO TIME REFERENCE DATA		1 DAY		3 DAYS		7 DAYS		14 DAYS	
	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation
3.6	9100	93.1	9520	203	9790	59.3	10300	325	10700	55.2
10	5860	19.9	6010	151	6130	143	6450	190	6650	24.1
20	5270	29.0	5430	118	5520	122	5760	141	5940	11.7
50	4720	17.2	4870	75.8	4930	96.5	6510	114	5270	20.0
100	4400	50.8	4530	101	4490	147	4750	114	4890	39.3
500	3770	64.1	3950	197	3860	102	4140	75.8	4260	78.6
700	3660	71.0	3800	223	3750	82.1	4030	40.4	4100	43.8
1000	3520	66.9	3630	247	3610	87.6	3900	51.0	3990	79.3
1100	3500	59.3	3560	263	3590	87.6	3860	44.1	3950	87.6
1200	3480	60.0	3510	267	3570	91.7	3830	51.0	3920	91.7

[a] kN/m^2

TABLE VIII-b

STRESS RELAXATION TESTS AT 40% RELATIVE HUMIDITY
AND 25°C (3% Strain Level)
Recovery at 0% Relative Humidity Following
14 Days Soak at 40% Relative Humidity

TIME (seconds)	ZERO TIME REFERENCE DATA		1 DAY		3 DAYS		7 DAYS	
	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation
3.6	10700	55.2	10300	219	9860	39.3	9240	403
10	6650	24.1	6360	86.2	6130	51.7	5830	210
20	5940	11.7	5710	98.6	5480	37.9	5250	189
50	5270	20.0	5080	125	4900	29.0	4700	165
100	4890	39.3	4710	108	4540	45.5	4450	67.6
500	4260	78.6	4180	56.5	4070	62.7	3890	166
700	4100	43.8	4040	75.8	3950	27.9	3730	170
1000	3990	79.3	3830	71.0	3800	40.7	3610	143
1100	3950	87.6	3810	66.9	3760	26.2	3570	145
1200	3920	91.7	3780	97.2	3740	17.2	3540	150

[a]kN/m^2

TABLE IX-a

STRESS RELAXATION TESTS AT

70% RELATIVE HUMIDITY AND 25°C (3% Strain Level)

TIME (seconds)	ZERO TIME REFERENCE DATA		1 DAY		3 DAYS		7 DAYS		14 DAYS	
	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation
3.6	9100	93.1	9100	197	9240	619	9240	95.8	8690	35.9
10	5860	19.9	5700	101	5900	31.7	5720	51.7	5430	108
20	5270	29.0	5120	93.1	5280	27.6	5110	48.3	4860	110
50	4720	17.2	4540	102	4710	11.7	4570	20.0	4440	82.7
100	4400	50.8	4220	97.9	4360	0.0	4300	51.7	4190	125
500	3770	64.1	3630	55.8	3690	27.6	3740	44.1	3540	85.5
700	3660	71.0	3520	59.3	3590	27.6	3650	39.3	3430	63.7
1000	3520	66.9	3400	53.8	3480	35.4	3520	8.3	3280	82.1
1100	3500	59.3	3360	54.5	3450	26.2	3470	20.7	3240	84.1
1200	3480	60.0	3310	87.6	3430	11.7	3440	27.6	3210	90.3

[a] kN/m^2

TABLE IX-b

STRESS RELAXATION TESTS AT

70% RELATIVE HUMIDITY AND 25°C (3% Strain Level)

Recovery at 0% Relative Humidity Following 14 Days
Soak at 70% Relative Humidity

TIME (seconds)	ZERO TIME REFERENCE DATA		1 DAY		3 DAYS		7 DAYS	
	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation
3.6	8690	35.9	8410	161	8960	311	9430	166
10	5430	108	5300	97.2	5520	166	5810	174
20	4860	110	4770	79.3	4950	170	5230	133
50	4440	82.7	4290	114	4570	37.9	4660	139
100	4190	125	4060	98.6	4250	114	4390	39.3
500	3540	85.5	3500	86.2	3610	138	3830	141
700	3430	63.7	3380	59.3	3520	131	3710	132
1000	3280	82.1	3250	65.5	3420	210	3580	125
1100	3240	84.1	3230	58.6	3380	195	3560	129
1200	3210	90.3	3210	59.3	3350	192	3520	139

[a]kN/m^2

TABLE X-a

STRESS RELAXATION TESTS AT

90% RELATIVE HUMIDITY AND 25°C (3% Strain Level)

TIME (seconds)	ZERO TIME REFERENCE DATA		1 DAY		3 DAYS		7 DAYS		14 DAYS	
	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation
3.6	9100	93.1	9380	101	8550	786	6620	440	4880	128
10	5860	19.9	5720	51.7	5170	323	4050	274	3130	84.1
20	5270	29.0	5120	29.0	4620	244	3620	218	2790	73.1
50	4720	17.2	4560	20.0	4120	190	3230	200	2450	83.4
100	4400	50.8	4220	40.7	3870	170	3010	205	2250	75.8
500	3770	64.1	3610	62.1	3410	121	2610	191	195	71.7
700	3660	71.0	3460	51.7	3250	194	2520	174	1890	39.3
1000	3520	66.9	3310	40.7	3060	170	2390	155	1870	15.9
1100	3500	59.3	3270	48.4	3020	173	2350	144	1850	30.3
1200	3480	60.0	3230	48.3	2990	159	2330	142	1840	35.2

[a] kN/m^2

TABLE X-b

STRESS RELAXATION TESTS AT

90% RELATIVE HUMIDITY AND 25°C (3% Strain Level)

Recovery at 0% Relative-Humidity Following 14 Days
At 90% Relative Humidity

TIME (seconds)	ZERO TIME REFERENCE DATA		1 DAY		3 DAYS		7 DAYS	
	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation	[a]Modulus (average)	Deviation
3.6	4880	128	5250	277	4870	53.8	6020	331
10	3130	84.1	3410	128	3230	87.6	4060	210
20	2790	73.1	3050	124	33.1	73.1	3660	183
50	2450	83.4	2690	97.9	2520	82.7	3240	145
100	2250	75.8	2470	76.5	2320	82.7	2990	149
500	195	71.7	2060	55.8	1960	58.6	2520	145
700	1890	39.3	1990	31.7	1900	73.1	2430	138
1000	1870	15.9	1930	31.7	1850	39.3	2330	114
1100	1850	30.3	1910	34.5	1850	39.3	2300	96.5
1200	1840	35.2	1900	31.0	1850	39.3	2270	93.8

[a] kN/m^2

TABLE XI-a

DYNAMIC TENSION TESTS AT 40% RELATIVE HUMIDITY

AND 25°C (1% Static Strain)

STORAGE TIME	3.5 Hz				11. Hz				35 Hz				110 Hz			
	T_{A_N} δ	|E| $\left(\frac{MN}{m^2}\right)$	|E'| $\left(\frac{MN}{m^2}\right)$	|E"| $\left(\frac{MN}{m^2}\right)$	T_{A_N}	|E| $\left(\frac{MN}{m^2}\right)$	|E'| $\left(\frac{MN}{m^2}\right)$	|E"| $\left(\frac{MN}{m^2}\right)$	T_{A_N}	|E| $\left(\frac{MN}{m^2}\right)$	|E'| $\left(\frac{MN}{m^2}\right)$	|E"| $\left(\frac{MN}{m^2}\right)$	T_{A_N}	|E| $\left(\frac{MN}{m^2}\right)$	|E'| $\left(\frac{MN}{m^2}\right)$	|E"| $\left(\frac{MN}{m^2}\right)$
0	.43	12.6	11.6	4.67	.47	14.0	12.6	6.0	.62	21.8	18.5	11.4	.58	31.1	26.8	15.8
$^1D_{A_Y}$	.395	22.5	20.8	8.26	.425	28.4	26.2	11.1	.708	27.8	22.8	15.9	.546	57	50	27.4
$^3D_{A_{Y_S}}$	.416	22	20.3	8.44	.455	28.2	25.7	11.7	.541	36.5	32.1	17.2	.579	57	49.3	28.5
$^7D_{A_{Y_S}}$	.39	17.2	16.0	6.24	.421	21.5	19.8	8.34	.71	20.5	14.0	14.3	.566	45	39.4	22.2
$^{14}D_{A_{Y_S}}$	.396	19.8	18.4	7.27	.424	24.8	22.6	9.69	.88	22.4	17.1	14.2	.56	52.2	45.6	25.5
1 DAY RECOVERY	.406	18.6	17.1	6.95	.439	23.5	21.5	9.48	.91	24.6	16.5	18.0	.601	53.5	45.8	27.5
3 DAYS RECOVERY	.403	21.1	19.6	7.88	.425	26.4	24.3	10.5	.97	26.4	19.1	18.0	.556	54	47.2	26.3
7 DAYS RECOVERY	.365	22.6	21.2	7.73	.4	27.6	25.6	10.2	.735	25.1	22.2	11.4	.548	59.1	51.8	28.4

TABLE X1-b

DYNAMIC TENSION TESTS AT 70% RELATIVE HUMIDITY

AND 25°C (1% Static Strain)

STORAGE TIME	3.5 Hz				11. Hz				35 Hz				110 Hz			
	T_{A_N} δ	|E| $\left(\frac{MN}{m^2}\right)$	|E'| $\left(\frac{MN}{m^2}\right)$	|E''| $\left(\frac{MN}{m^2}\right)$	T_{A_N} δ	|E| $\left(\frac{MN}{m^2}\right)$	|E'| $\left(\frac{MN}{m^2}\right)$	|E''| $\left(\frac{MN}{m^2}\right)$	T_{A_N} δ	|E| $\left(\frac{MN}{m^2}\right)$	|E'| $\left(\frac{MN}{m^2}\right)$	|E''| $\left(\frac{MN}{m^2}\right)$	T_{A_N} δ	|E| $\left(\frac{MN}{m^2}\right)$	|E'| $\left(\frac{MN}{m^2}\right)$	|E''| $\left(\frac{MN}{m^2}\right)$
0	.43	12.6	11.6	4.67	.47	14.0	12.6	6.0	.62	21.8	18.5	11.4	.58	31.1	26.8	15.8
$^1D_{A_Y}$	.403	15.9	14.7	5.92	.433	19.9	18.3	9.94	.87	17.9	13.6	11.4	.558	40.4	34.9	20.2
$^3D_{A_{Y_S}}$	.439	20.2	18.5	8.13	.469	26.4	23.9	11.2	.575	34.7	30.2	17.2	.59	52.3	45.2	26.6
$^7D_{A_{Y_S}}$	.403	16.3	15.1	6.09	.439	20.2	18.5	8.69	1.26	19.8	12.8	14.8	.579	41.6	36.1	20.9'
$^{14}D_{A_{Y_S}}$	.409	13.4	12.4	5.07	.441	17.1	15.7	6.91	1.65	23.6	12.2	20.2	.606	38	32.4	19.8
1 DAY RECOVERY	.414	16.6	15.3	6.33	.445	21	19.2	8.55	1.43	21.9	13.9	16.8	.594	45.2	38.9	23.1
3 DAYS RECOVERY	.386	21.6	20.1	7.79	.406	26.7	24.8	10.0	1.4	22.4	13.7	17.3	.544	54.8	48.1	26.1
7 DAYS RECOVERY	.361	22.5	21.1	7.64	.391	27.1	25.2	9.89	.84	22.4	18.2	13.9	.554	58.5	51.2	28.4

TABLE X1-c

DYNAMIC TENSION TESTS AT 90% RELATIVE HUMIDITY

AND 25°C (1% Static Strain)

STORAGE TIME	3.5 Hz				11. Hz				35 Hz				110 Hz			
	T_{A_N} δ	|E| $\left(\frac{MN}{m^2}\right)$	|E'| $\left(\frac{MN}{m^2}\right)$	|E''| $\left(\frac{MN}{m^2}\right)$	T_{A_N} δ	|E| $\left(\frac{MN}{m^2}\right)$	|E'| $\left(\frac{MN}{m^2}\right)$	|E''| $\left(\frac{MN}{m^2}\right)$	T_{A_N} δ	|E| $\left(\frac{MN}{m^2}\right)$	|E'| $\left(\frac{MN}{m^2}\right)$	|E''| $\left(\frac{MN}{m^2}\right)$	T_{A_N} δ	|E| $\left(\frac{MN}{m^2}\right)$	|E'| $\left(\frac{MN}{m^2}\right)$	|E''| $\left(\frac{MN}{m^2}\right)$
0	.43	12.6	11.6	4.67	.47	14.0	12.6	6.0	.62	21.8	18.5	11.4	.58	31.1	26.8	15.8
$^1D_{A_Y}$	.47	4.38	3.96	1.86	.489	5.83	5.23	2.56	.855	8.55	6.46	5.88	.85	11.2	8.63	7.14
$^3D_{A_{Y_S}}$	.493	2.44	2.19	1.09	.531	2.96	2.62	1.4	.643	3.91	3.25	2.16	.745	8.83	7.09	5.33
$^7D_{A_{Y_S}}$		< 1				< 1				< 1			.618	1.6	1.36	.84
$^{14}D_{A_{Y_S}}$		< 1				< 1				< 1			.62	.82	.70	.43
1 DAY RECOVERY		< 1				< 1				< 1			.581	1.82	1.57	.91
3 DAYS RECOVERY	.375	4.8	4.49	1.69	.385	6.26	6.09	2.26	1.29	10.2	6.43	7.8	.524	12.2	10.8	5.66
7 DAYS RECOVERY	.324	1.28	12.1	3.89	.334	15.4	14.6	4.85	1.42	10.0	5.81	8.15	.503	34.8	31.1	1.57

TABLE XII-a

DYNAMIC SHEAR TESTS AT 40% RELATIVE HUMIDITY

AND 25°C (1% Static Strain)

STORAGE TIME	3.5 Hz				11. Hz				35 Hz				110 Hz			
	$T_{AN}\delta$	$\lvert E\rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E'\rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E''\rvert$ $\left(\frac{MN}{m^2}\right)$	$T_{AN}\delta$	$\lvert E\rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E'\rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E''\rvert$ $\left(\frac{MN}{m^2}\right)$	$T_{AN}\delta$	$\lvert E\rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E'\rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E''\rvert$ $\left(\frac{MN}{m^2}\right)$	$T_{AN}\delta$	$\lvert E\rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E'\rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E''\rvert$ $\left(\frac{MN}{m^2}\right)$
0	.33	3.44	3.27	1.05	.27	6.0	5.78	1.55	.41	3.8	3.52	1.43	.34	9.77	9.25	3.08
$^1D_{A_Y}$	.161	6.56	6.44	1.23	.171	7.18	7.11	1.28	.163	4.83	4.75	.87	.22	12.4	12.1	2.71
$^3D_{A_{Y_S}}$	.243	7.32	7.08	1.70	.225	8.37	8.19	1.82	.155	7.05	7.0	.93	.32	14.0	13.3	4.23
$^7D_{A_{Y_S}}$	.193	6.76	6.65	1.24	.178	7.52	7.4	1.26	.127	5.45	5.42	.63	.20	12.6	12.4	2.36
$^{14}D_{A_{Y_S}}$	.202	6.54	6.41	1.28	.183	7.32	7.2	1.3	.145	6.0	5.92	.94	.189	11.1	10.9	2.04
1 DAY RECOVERY	.194	7.51	7.37	1.39	.175	8.28	8.14	1.42	.158	6.87	6.73	1.22	.234	13.6	13.3	3.23
3 DAYS RECOVERY	.16	5.62	5.55	.89	.145	6.1	6.03	.88	.11	3.34	3.33	.35	.174	9.47	9.32	1.66
7 DAYS RECOVERY	.17	5.4	5.32	0.93	.158	5.89	5.81	.94	.128	4.63	4.58	.67	.18	9.18	9.02	1.66

TABLE XII-b

DYNAMIC SHEAR TESTS AT 70% RELATIVE HUMIDITY AND 25°C (1% Static Strain)

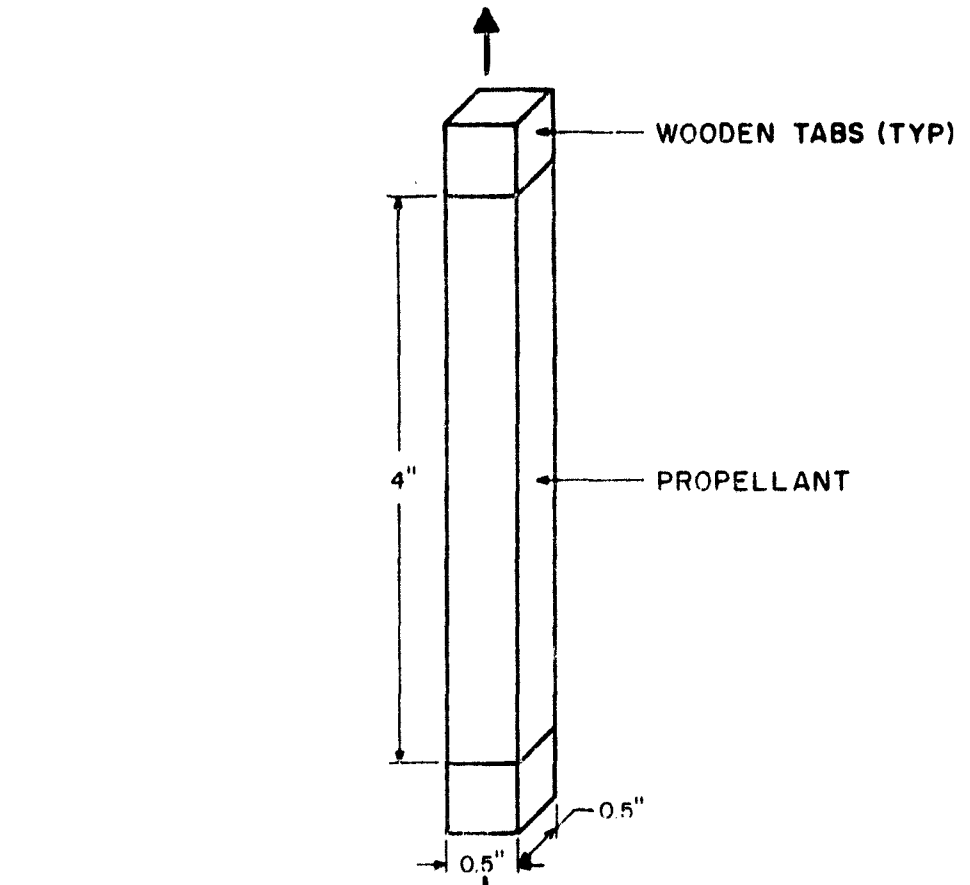
STORAGE TIME	3.5 Hz				11. Hz				35 Hz				110 Hz			
	T_{A_N} δ	$\lvert E \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E' \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E'' \rvert$ $\left(\frac{MN}{m^2}\right)$	T_{A_N} δ	$\lvert E \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E' \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E'' \rvert$ $\left(\frac{MN}{m^2}\right)$	T_{A_N} δ	$\lvert E \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E' \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E'' \rvert$ $\left(\frac{MN}{m^2}\right)$	T_{A_N} δ	$\lvert E \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E' \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E'' \rvert$ $\left(\frac{MN}{m^2}\right)$
0	.33	3.44	3.27	1.05	.27	6.0	5.78	1.55	.41	3.8	3.52	1.43	.34	9.77	9.25	3.08
$^1D_{A_Y}$	.194	8.8	8.61	1.54	.174	9.66	9.51	1.54	.181	5.55	5.45	.96	.276	15.4	14.8	3.89
$^3D_{A_{Y_S}}$	.224	6.48	6.33	1.4	.201	7.33	7.23	1.44	.139	3.45	3.4	.47	.30	13.0	12.5	3.69
$^7D_{A_{Y_S}}$	.244	4.8	4.66	1.15	.226	5.47	5.33	1.23	.169	6.25	6.15	1.08	.239	8.8	8.55	2.05
$^{14}D_{A_{Y_S}}$	.206	6.51	6.37	1.31	.188	7.37	7.24	1.36	.153	5.17	5.09	.9	.235	14.0	13.6	3.56
1 DAY RECOVERY	.248	5.81	5.69	1.26	.225	6.51	6.37	1.28	.155	4.5	4.43	.79	.264	10.4	10.1	2.26
3 DAYS RECOVERY	.17	6.21	6.12	1.02	.156	6.76	6.68	1.02	.118	5.8	5.75	.72	.179	9.38	9.23	1.61
7 DAYS RECOVERY	.229	5.14	5.51	1.15	.213	5.78	5.65	1.21	.173	3.52	3.47	.58	.226	9.16	8.93	2.05

TABLE XII-c

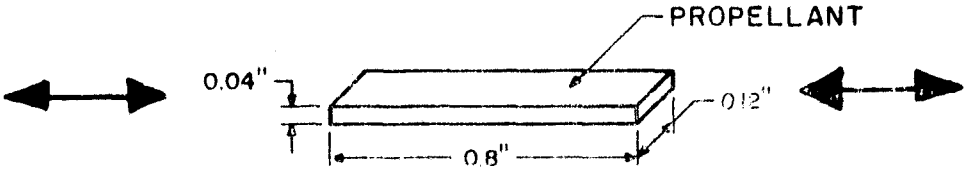
DYNAMIC TENSION TESTS AT 90% RELATIVE HUMIDITY

AND 25°C (1% Static Strain)

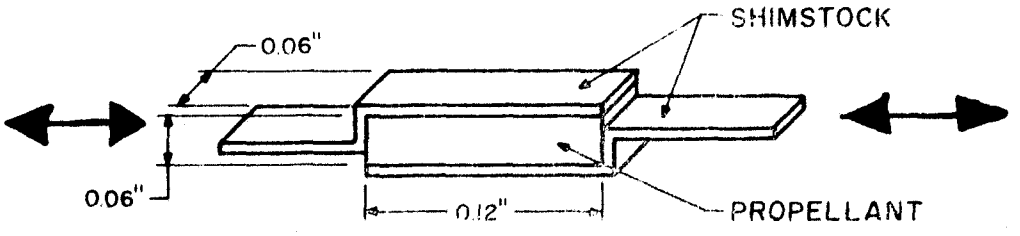
STORAGE TIME	3.5 Hz				11. Hz				35 Hz				110 Hz			
	T_{A_N} δ	$\lvert E \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E' \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E'' \rvert$ $\left(\frac{MN}{m^2}\right)$	T_{A_N} δ	$\lvert E \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E' \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E'' \rvert$ $\left(\frac{MN}{m^2}\right)$	T_{A_N} δ	$\lvert E \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E' \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E'' \rvert$ $\left(\frac{MN}{m^2}\right)$	T_{A_N} δ	$\lvert E \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E' \rvert$ $\left(\frac{MN}{m^2}\right)$	$\lvert E'' \rvert$ $\left(\frac{MN}{m^2}\right)$
0	.33	3.44	3.27	1.05	.27	6.0	5.78	1.55	.41	3.8	3.52	1.42	.34	9.77	9.25	3.08
$^1D_{A_Y}$	.449	.79	.73	.32	.474	1.06	.96	.44	.456	1.30	1.18	.53	.519	1.89	1.69	.84
$^3D_{A_{Y_S}}$	.42	.58	.54	.22	.459	.74	.68	.31	.419	.90	.83	.35	.52	1.26	1.12	.57
$^7D_{A_{Y_S}}$		< 1				< 1				< 1			.557	1.08	.92	.55
$^{14}D_{A_{Y_S}}$		< 1				< 1				< 1				< 1		
1 DAY RECOVERY		< 1				< 1				< 1				< 1		
3 DAYS RECOVERY	.398	1.18	1.09	.46	.379	1.43	1.33	.50	.30	1.33	1.27	.37	.463	2.02	1.82	.86
7 DAYS RECOVERY	.264	2.44	2.36	.59	.273	2.77	2.68	.70	.254	1.85	1.78	.50	.344	4.25	4.02	1.34



STATIC TEST SPECIMEN



DYNAMIC TENSION TEST SPECIMEN



DYNAMIC SHEAR TEST SPECIMEN

FIGURE 1 - Test Specimen Configurations

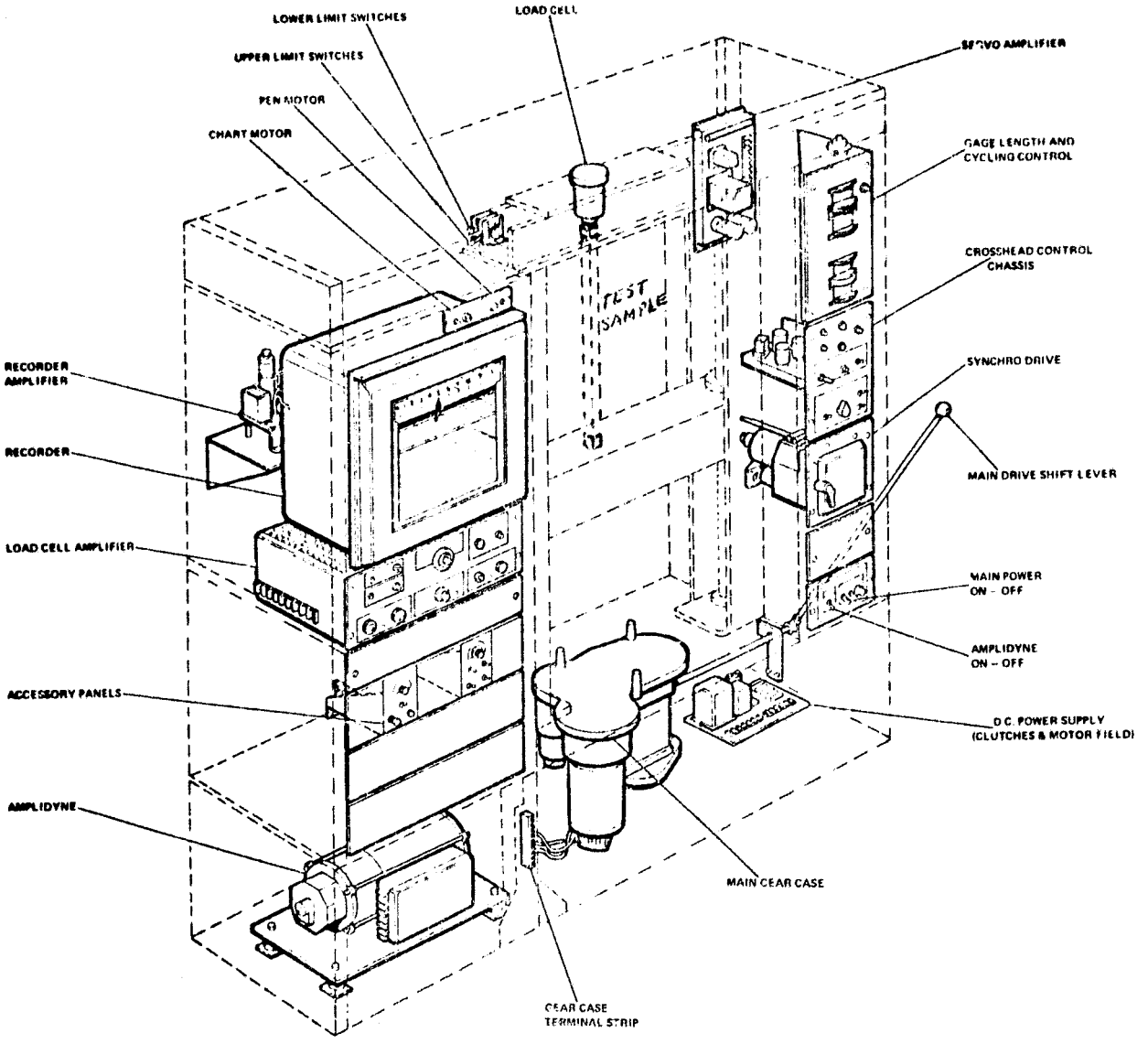


FIGURE 2 - Schematic of Instron
Universal Testing Machine

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

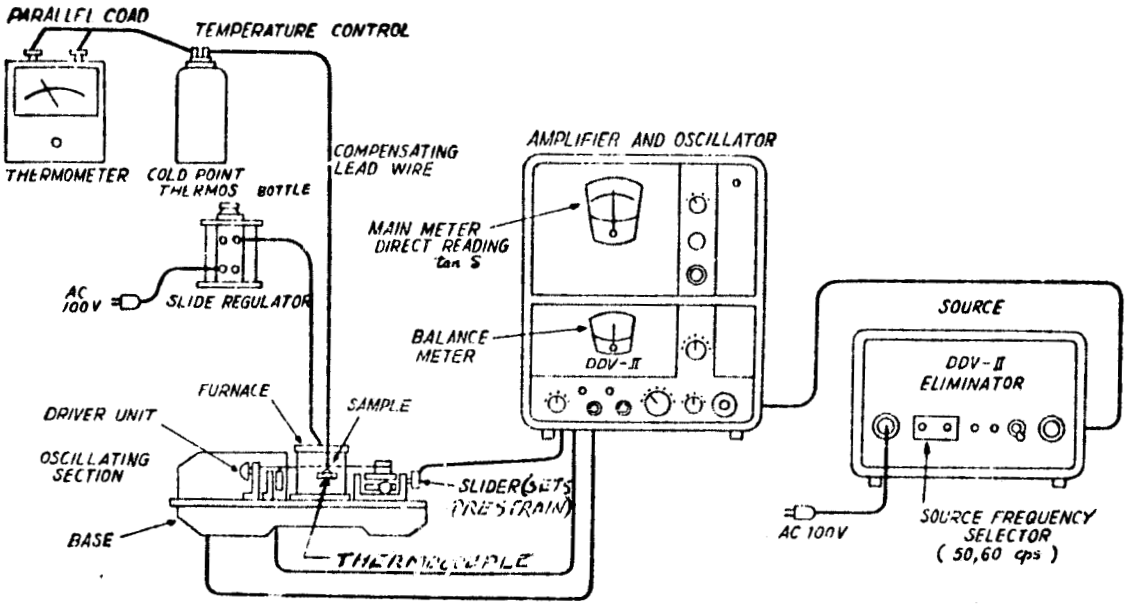


FIGURE 3 - Schematic of Rheovibron Dynamic Tester

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

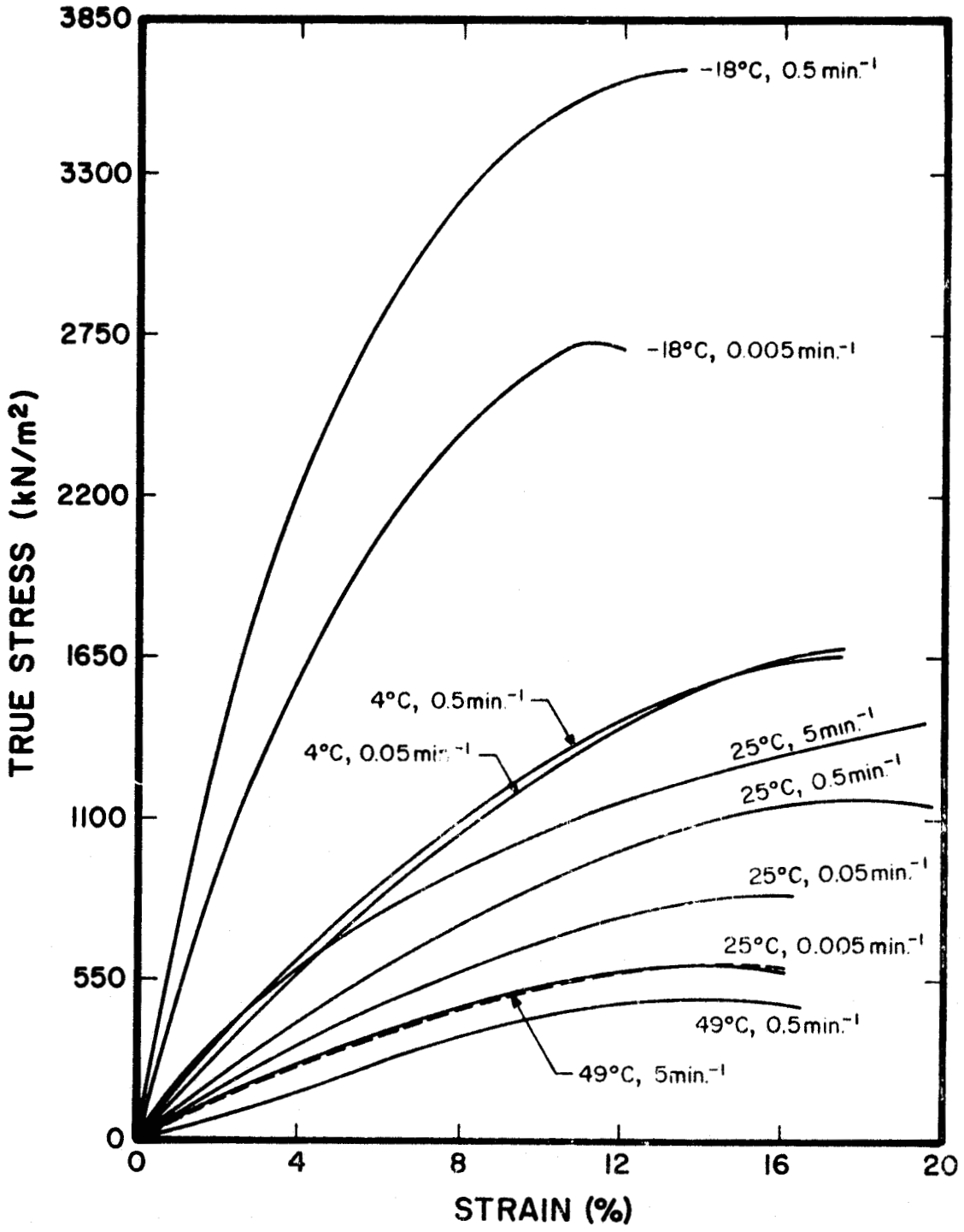


FIGURE 4 - True-Stress-Versus-Strain Response

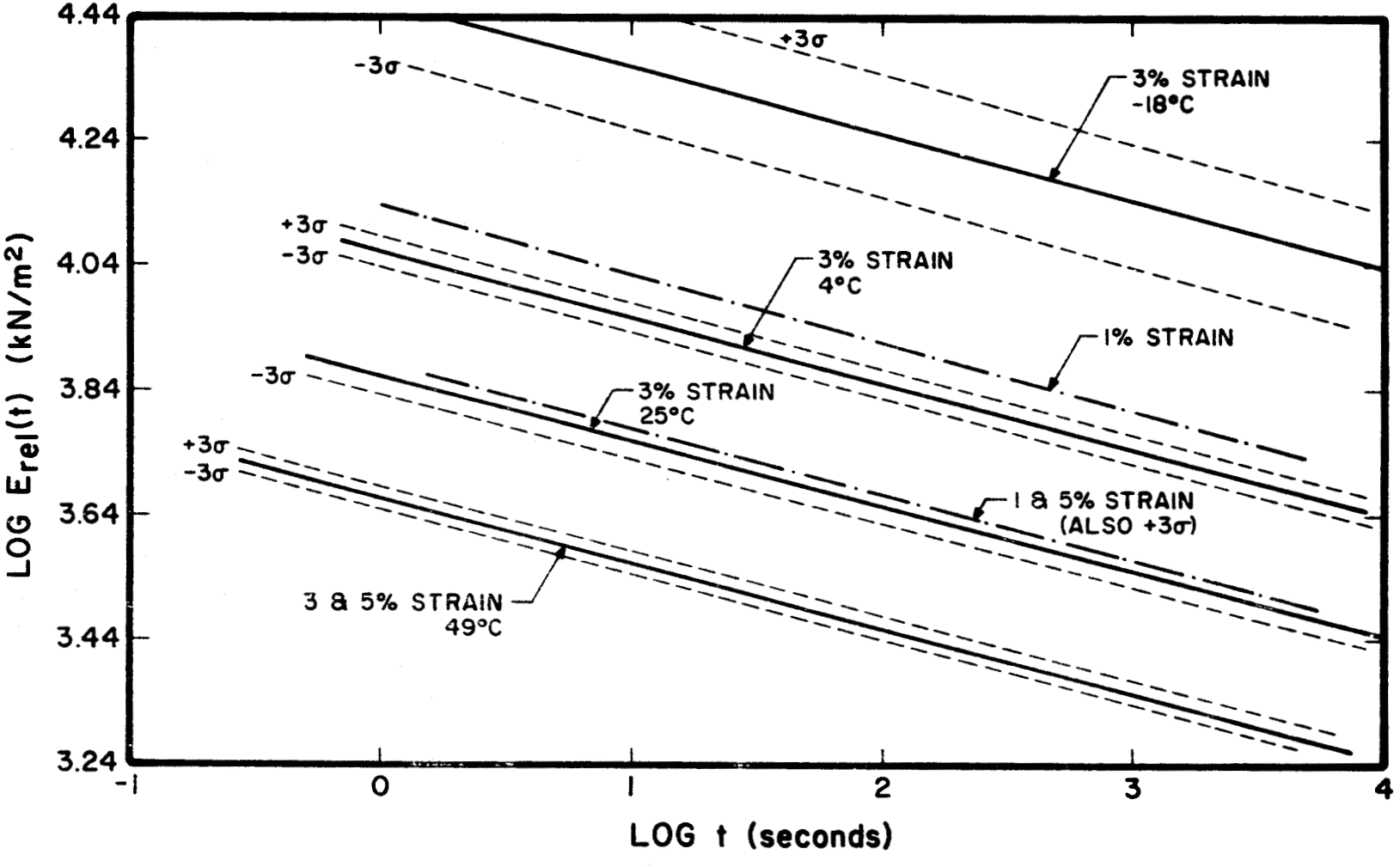


FIGURE 5 - Stress Relaxation Modulus Versus Log Time

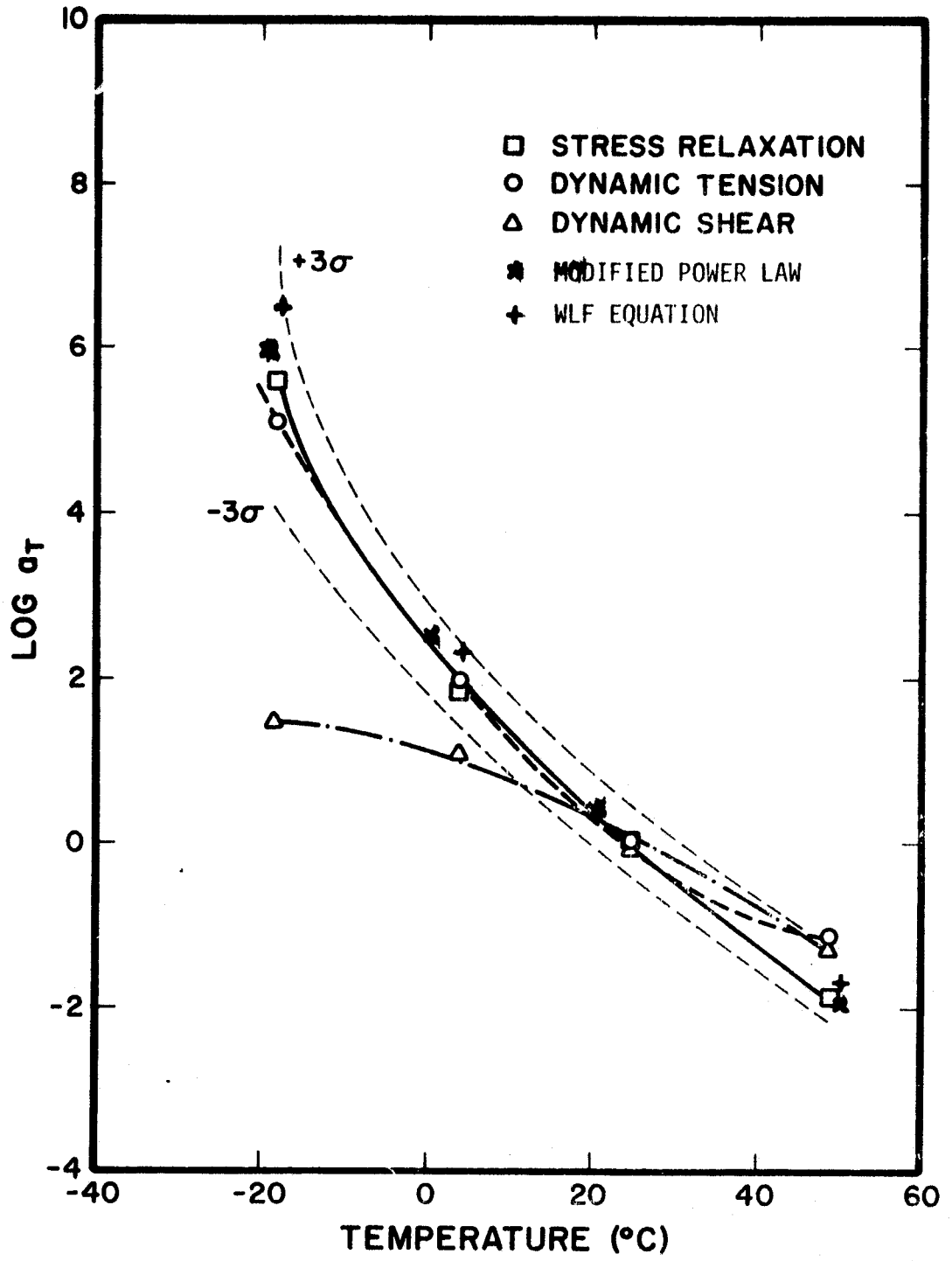


FIGURE 6 - Time-Temperature Shift Factor Versus Temperature

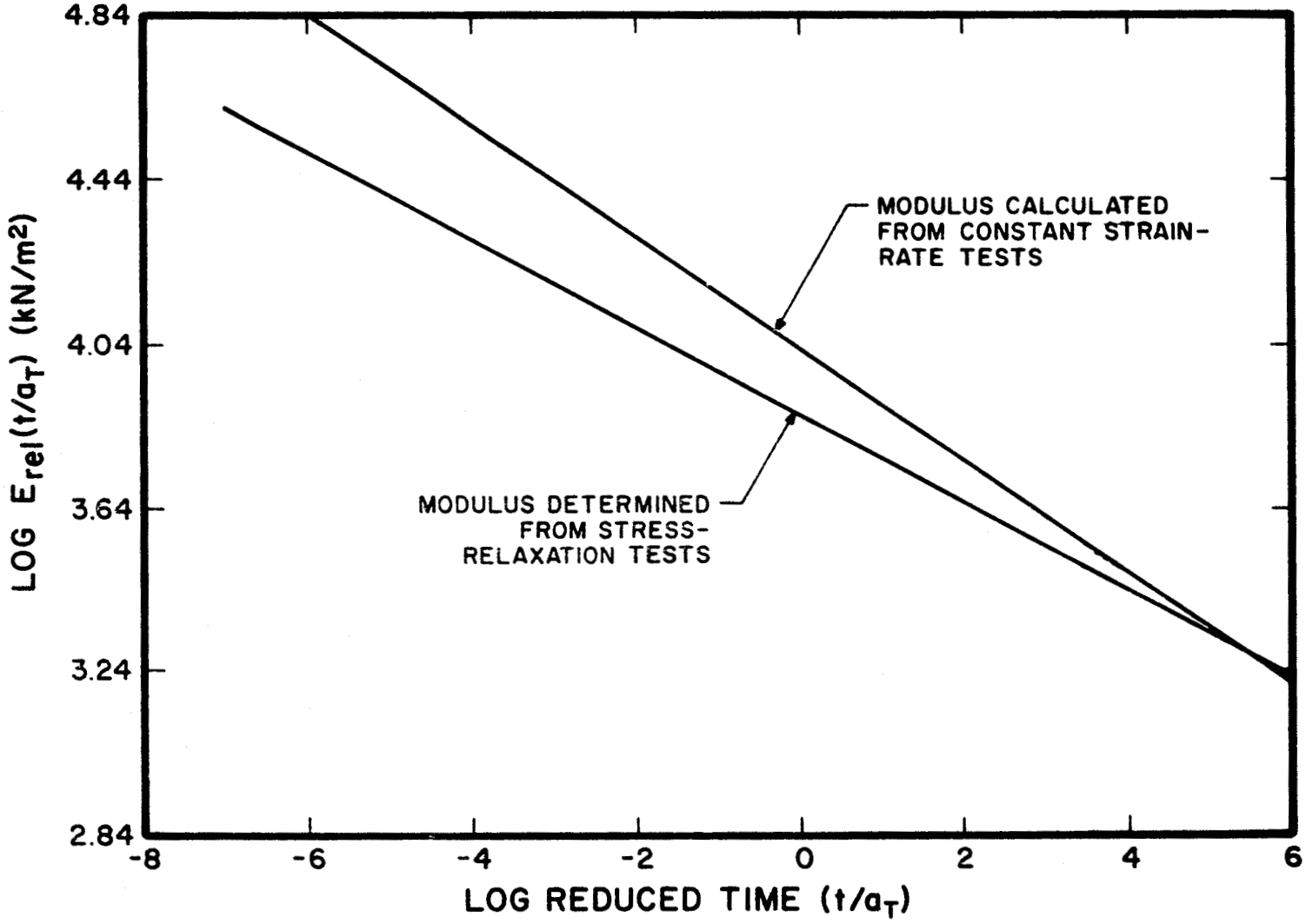


FIGURE 7 - Master Stress Relaxation Modulus Versus Temperature Reduced Time

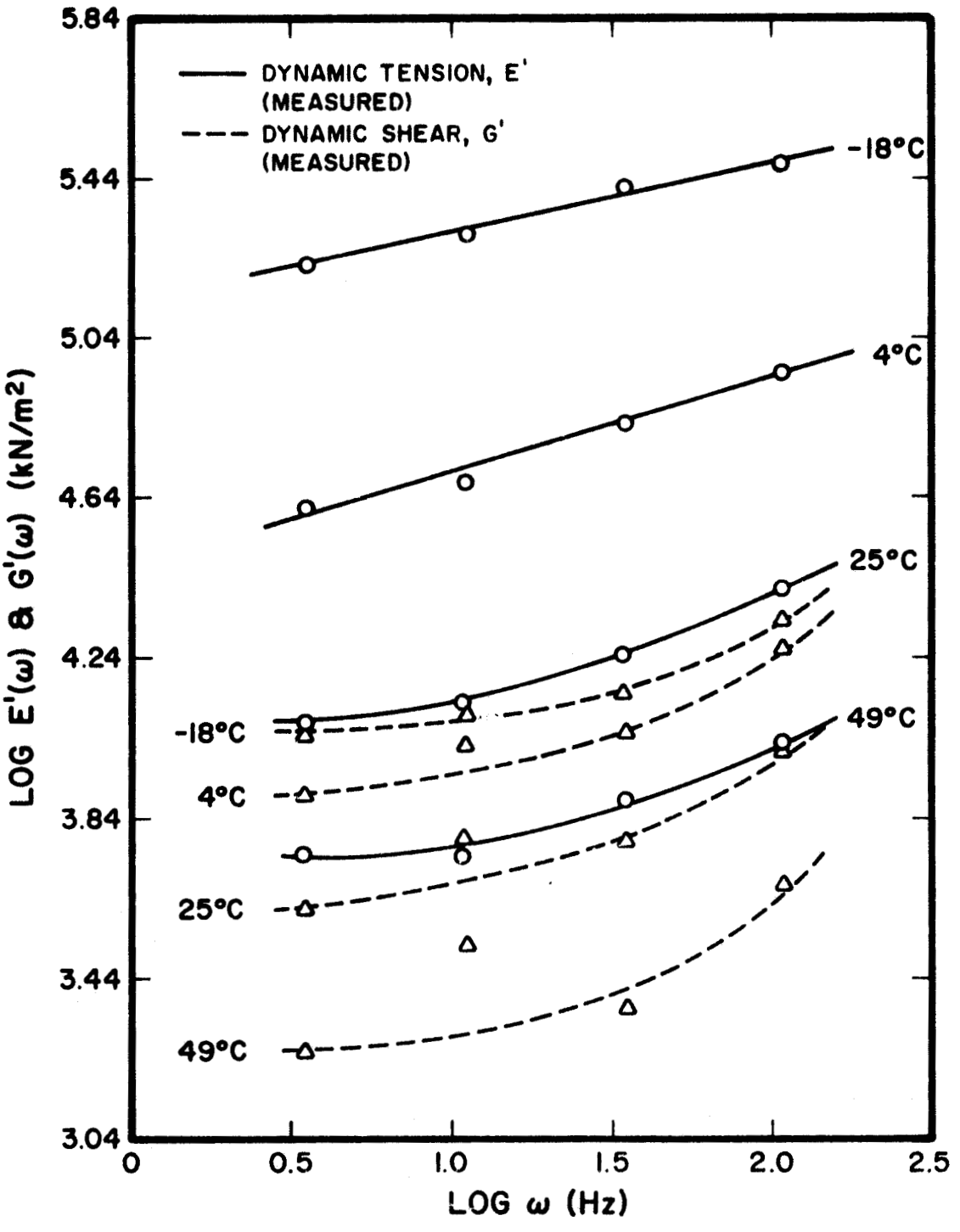


FIGURE 8 - REAL PART OF DYNAMIC TENSILE AND SHEAR MODULUS VERSUS FREQUENCY

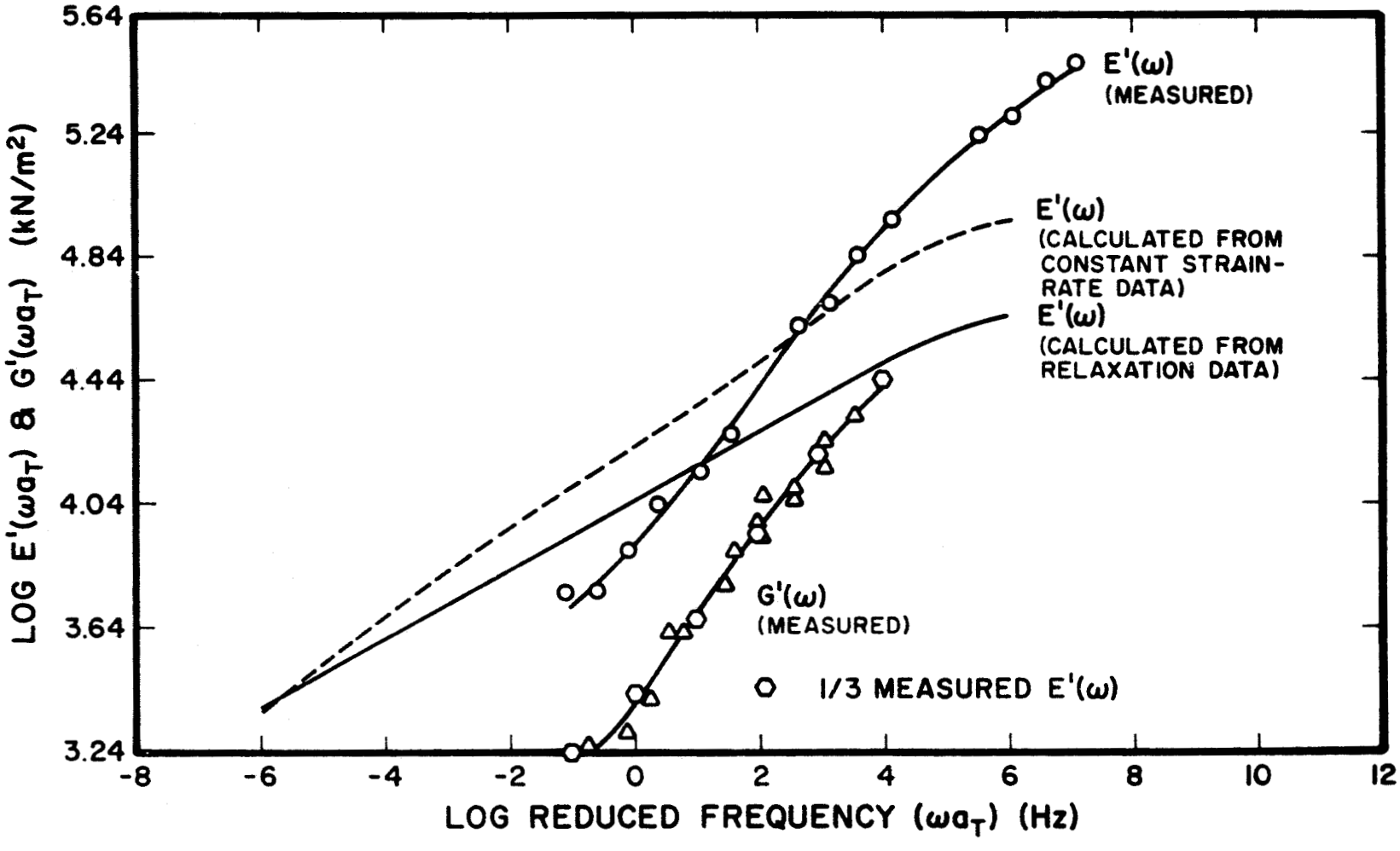


FIGURE 9 - MASTER DYNAMIC MODULUS VERSES
TEMPERATURE REDUCED FREQUENCY

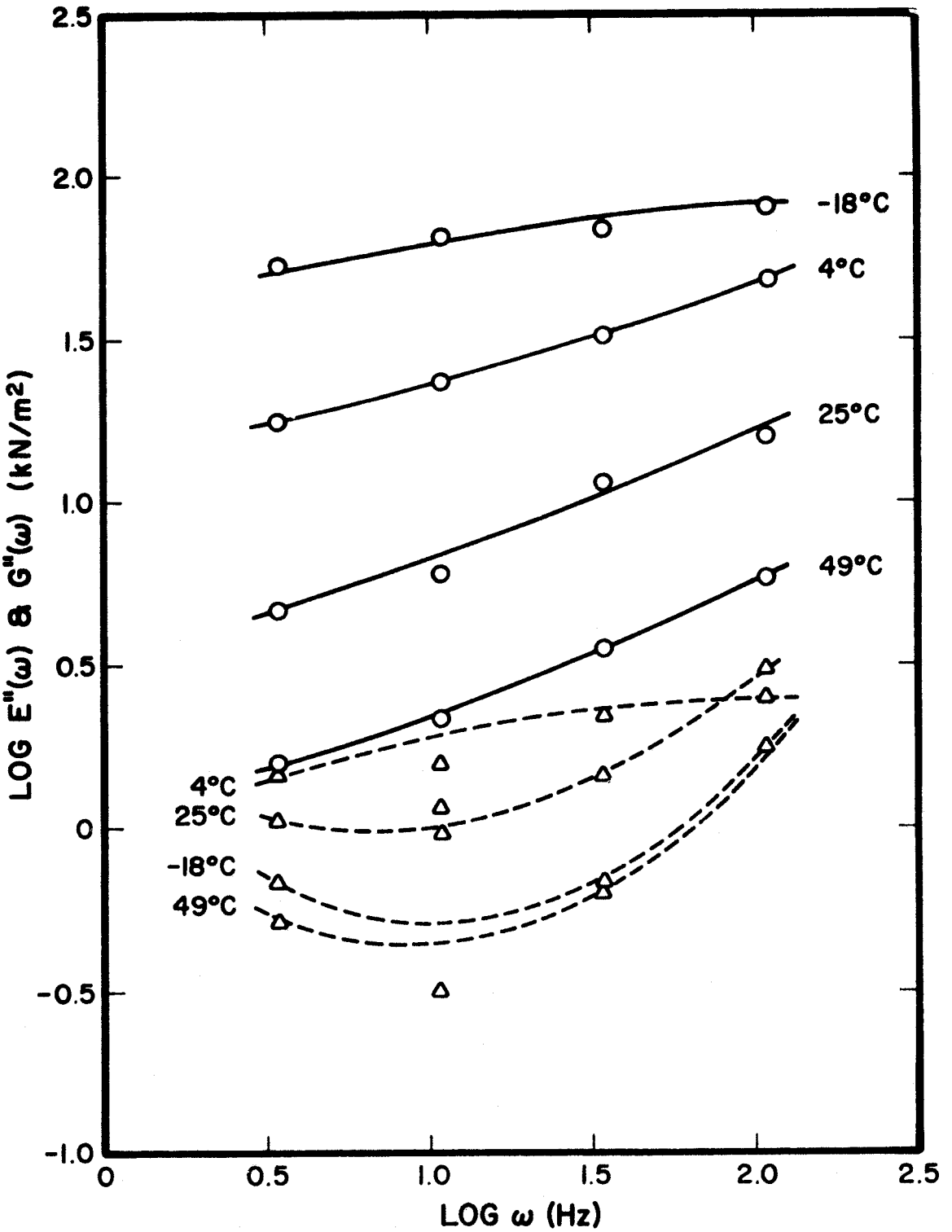


FIGURE 10- Imaginary Part of Dynamic Tensile & Shear Modulus Versus Frequency

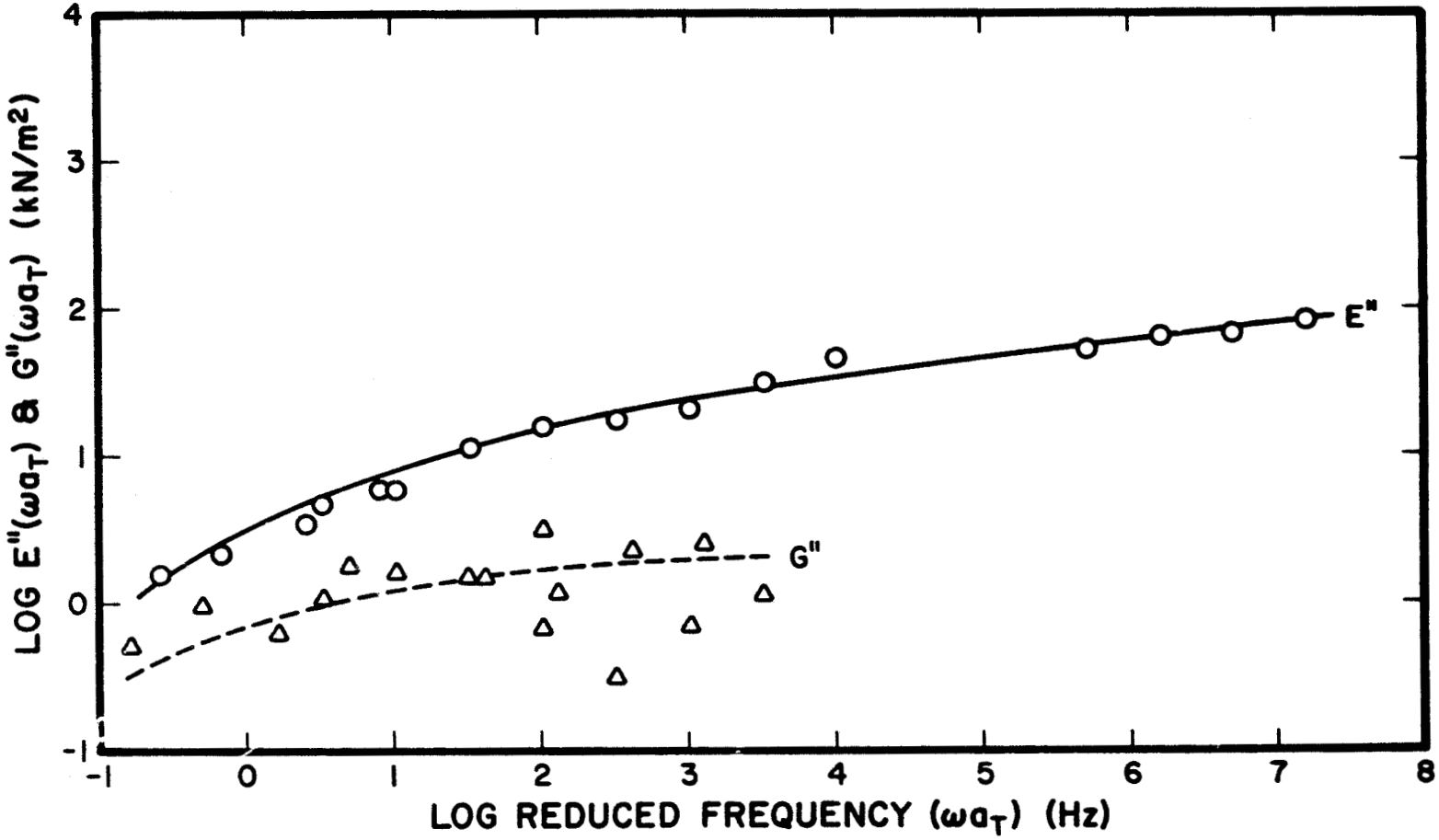


FIGURE 11 - Master Dynamic Loss Modulus Versus Temperature Reduced Frequency

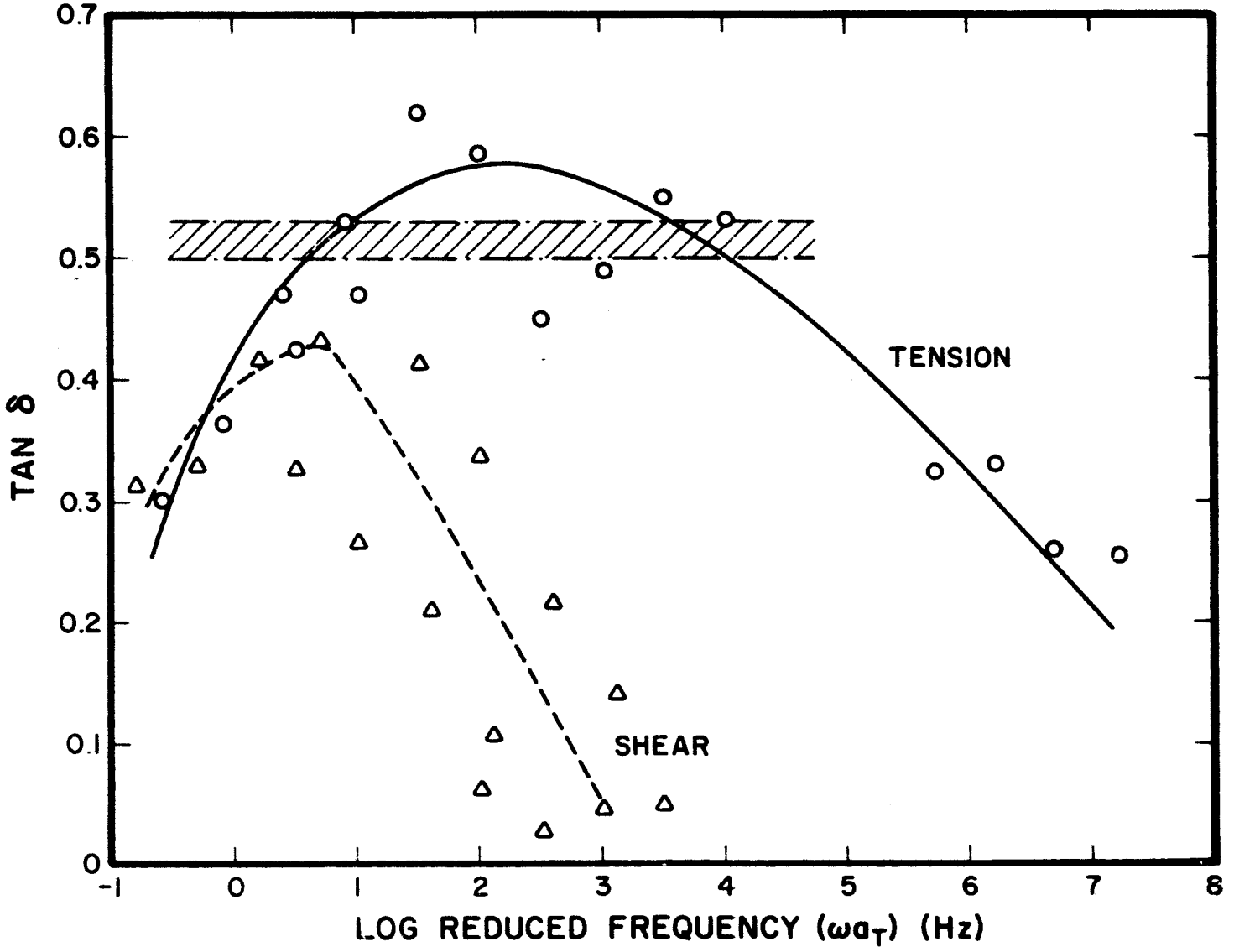


FIGURE 12 - Loss Tangent Versus Temperature Reduced Frequency